THE STATE OF
Carbon Dioxide Removal

A global, independent scientific assessment of Carbon Dioxide Removal

3rd EDITION | 2026

A collaboration led by Morgan R. Edwards (University of Wisconsin-Madison), Oliver Geden (German Institute for International and Security Affairs, SWP), Matthew J. Gidden (University of Maryland), William F. Lamb (Potsdam Institute for Climate Impact Research, PIK), Jan C. Minx (Potsdam Institute for Climate Impact Research, PIK), Gregory F. Nemet (University of Wisconsin-Madison) and Stephen M. Smith (University of Oxford).

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Front- and back cover: Aerial top-down view of a rocky seashore. By Petar Bonev

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Foreword

Sugerido pelos organizadores com comentários e edições da Presidência da COP30 (gabinete + Agenda de Ação)

We now live in a world experiencing the direct impacts of a changing climate. With recent individual years breaching 1.5°C, and as we approach this critical threshold, even greater ambition is urgently needed to keep the Paris Agreement's long-term temperature goal within reach of 1.5°C by end of the century.

The world's most pressing issue is reducing sources of emissions, and it is one of the foundations upon which climate action must be built. The outcome of the first Global Stocktake adopted at COP28 provides guidance on the key pillars of climate action that must be urgently acted upon. It calls on Parties, among other priorities, to contribute, in a nationally determined manner and in light of their respective national circumstances, to the global effort to transition away from fossil fuels in energy systems in a just, orderly and equitable way – accelerating action in this critical decade to achieve net zero by 2050. It also emphasizes the critical importance of protecting, conserving, and restoring nature, including halting and reversing deforestation and forest degradation by 2030.

To support the implementation of the Global Stocktake, the COP30 Presidency announced at the last Belem Plenary Session that it would develop two Roadmaps operationalizing the aformentioned decisions.

No doubt, carbon removal will serve as a key guiding instrument of these efforts, as it is also essential to the goals described in the Roadmaps. Science is clear that while reducing emissions is absolutely necessary, it is no longer sufficient. We must also urgently scale up approaches to actively remove legacy carbon dioxide from the atmosphere. Therefore, tracking our progress on carbon removal activities is critical.

In this respect, this 3rd Edition of the *State of Carbon Dioxide Removal* report plays an invaluable role, offering a sober assessment of where we are and the enormous distance we still need to go in the race to limit global temperature rise.

While it is certainly a race, we must be aware that, although important, we cannot afford a future that depends on uncertain technologies or that relies on unsustainable practices that harm ecosystems and communities in the name of carbon removal. Pursuing long-lasting, sustainable carbon removal requires combining the wisdom of conservation and justice with the promise of innovation. This means fostering synergy, not tension, between conventional approaches of carbon removal like protecting and restoring our forests, and novel approaches based on technology that can provide durable carbon removal.

This effort carries both great risks and great promises, particularly in the design of voluntary carbon markets and compliance regimes. If implemented soundly, with high integrity and transparency, these approaches can enable more equitable outcomes, directing finance and technology from the Global North to the Global South, and rewarding suppliers of innovative carbon removal and local communities for their ecosystem stewardship. If pursued without caution and robust governance, however, they risk deepening inequalities between countries and communities. Our approach to carbon removal must be a central part of our commitment to climate justice.

In this respect, harmonizing carbon accounting is essential to ensure high integrity of initiatives that drive global decarbonization. That is why carbon accounting was a key initiative under the COP30 Action Agenda. Fragmented methods increase costs and produce inconsistent results, which undermines trust. To address this issue, frameworks must align with the Global Stocktake's call for "environmental integrity, transparency, and consistency". Building these standards through inclusive processes based on global collaboration is the most promising way to create a reliable ecosystem for the advancement of carbon removal technologies and to increase trust in carbon markets.

The 3rd Edition of the *State of Carbon Dioxide Removal* provides a robust and useful perspective that the private sector, academia, and policymakers can look to for guidance. It is an important tool to help us navigate the complexities of this challenge as we move from a world of commitments to one of tangible, equitable and durable implementation.

Ana Toni,
CEO COP30

Executive summary

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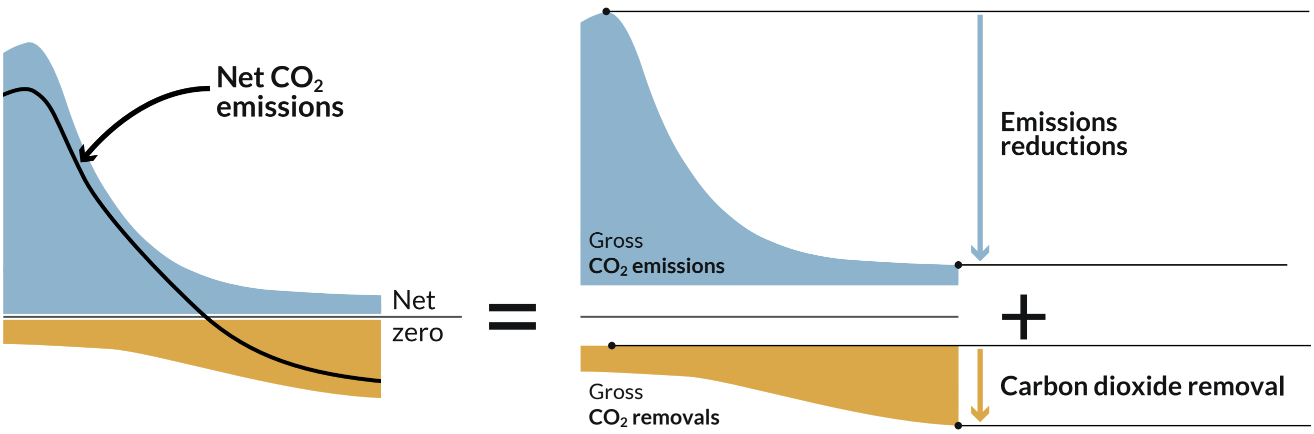
Aerial top-down view of a rocky seashore. By Petar Bonev

Executive summary

1. Both carbon dioxide removal (CDR) and emissions reductions are needed to reach the Paris temperature goal.

CDR consists of human activities capturing CO_2 from the atmosphere and storing it durably in geological, terrestrial or ocean reservoirs, or in products. For as long as any emissions continue, CDR will be needed to halt the rise in global temperature. All scenarios that reach net zero and halt the rise in global temperature deploy additional CDR at gigatonne scale. Across cost-effective scenarios compatible with the Paris Agreement, reductions in emissions contribute at least 80% of the effort to achieve net zero CO_2 emissions, and CDR contributes the remainder.

Both carbon dioxide removal (CDR) and emissions reductions are needed to reach climate targets



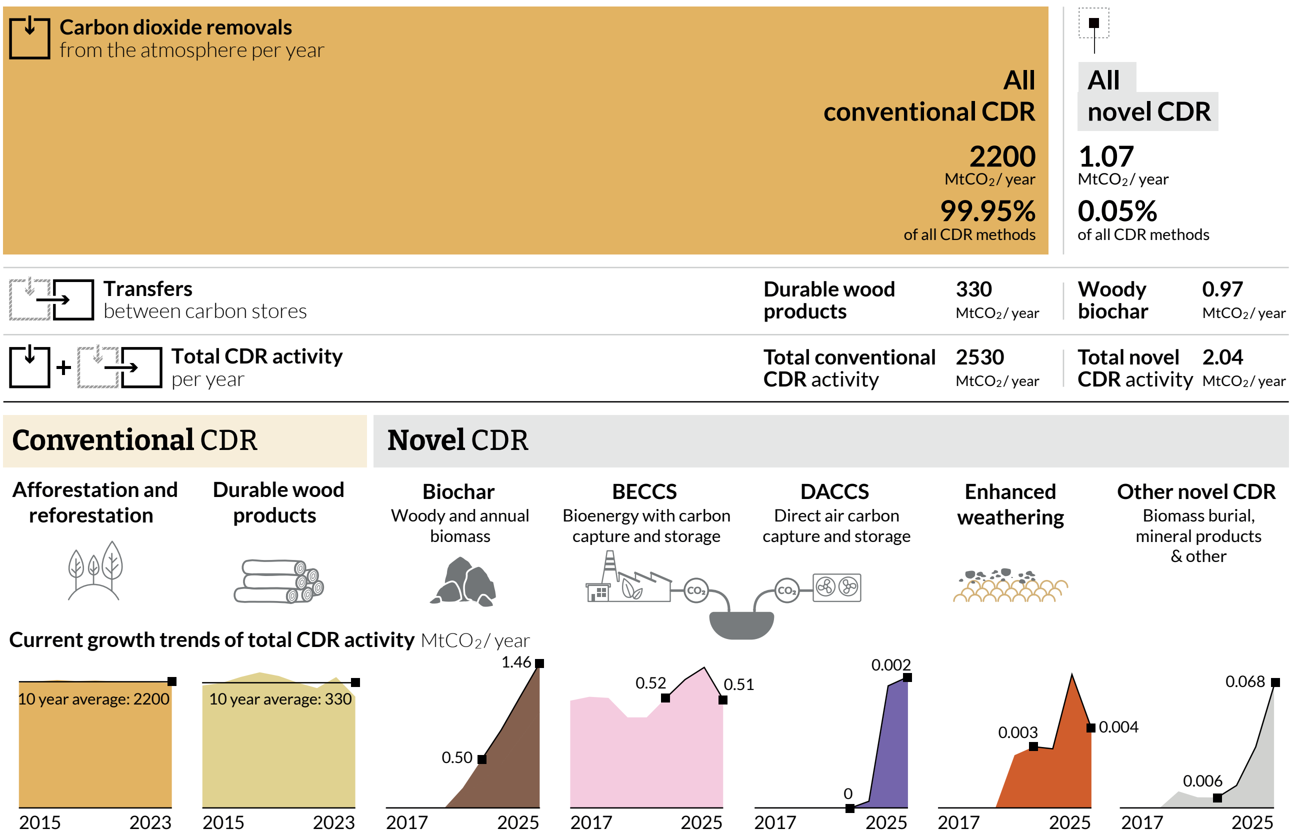
2. There are many CDR methods, and they span large ranges in costs, potentials and social acceptance.

CDR is comprised of “conventional CDR”, well-established methods that largely involve forests and soils, and “novel CDR,” such as biochar, enhanced weathering, and direct air carbon capture and storage. Expected costs for removals vary widely, from less than $10/tonne to over $1000/tonne, with most methods having upper limits exceeding $200/tonne, well above current carbon prices. Large dispersions in cost estimates exist even within each CDR method. For multiple methods, scale-up will depend on costs coming down. Independent removal potentials have similarly large ranges, with the more reliable lower range estimates for most methods around 1 $GtCO_2$ per year. Reasons for uncertainty include low scientific understanding, data availability, inconsistent definitions, and assumptions about sustainability and durability. Costs have those issues plus differences in system boundary definitions, and whether the co-benefits and the costs of monitoring, reporting, and verification are included. Public support is also uncertain. It involves concerns about eco-systems and governance, and depends on engaging diverse publics and conveying local benefits. Public familiarity with CDR is low, and news media coverage of CDR is down even though it is growing as a share of total climate coverage. For each method, proving reliability and effectiveness will be crucial to realizing potentials.

3. Current removal is almost entirely from land-based, conventional CDR; novel CDR is growing quickly but still comprises a tiny fraction of total removal.

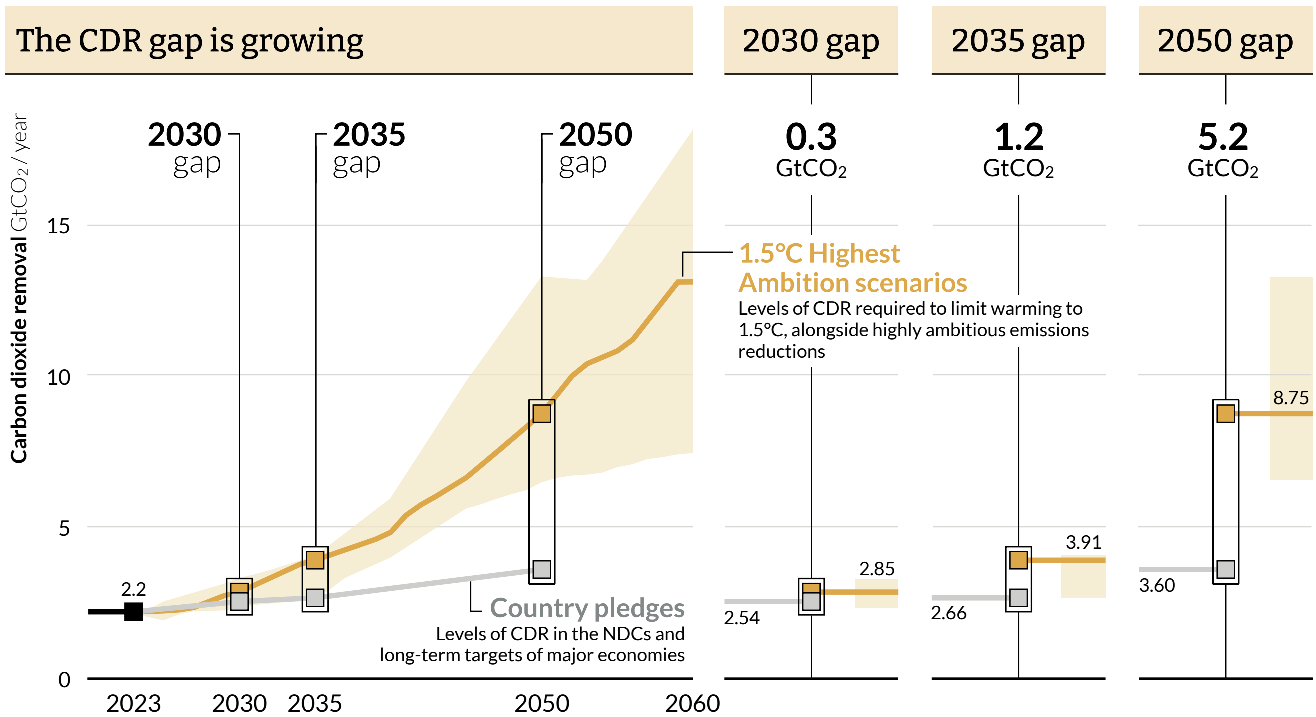
Total removal is 2.2 $GtCO_2$ per year, equivalent to 5% of gross CO_2 emissions. Conventional CDR represents 99.9% of this total, with the largest contributions from China, the United States, the European Union, Brazil and Russia. Novel CDR is 0.002 $GtCO_2$ per year and has been growing at 40% per year – similar to successful technologies like solar energy but insufficient for the scale-up required to meet the Paris temperature goal. Biochar and BECCS account for almost all novel removals. These projects plus those in construction would reach 0.008 $GtCO_2$ per year of capacity in 2030, although only 20% of planned capacity has been built in recent years.

Current CDR is almost entirely from conventional, but novel methods are growing



4. A large and growing gap exists between the amount of CDR in country pledges and that in Paris-compatible scenarios; both conventional and novel CDR are deployed in every scenario.

Country pledges, taking into account the latest nationally determined contributions, reach 2.5 $GtCO_2$ per year CDR in 2030 – but the median level in the highest-ambition Paris-compatible scenarios is 2.9 $GtCO_2$ per year. This results in a gap of 0.3 $GtCO_2$ per year. To close the 2030 gap, overall ambition needs to roughly double (i.e. from +0.3 $GtCO_2$ per year to +0.6 $GtCO_2$ per year in 2030) through new and revised pledges. The gap rapidly grows to 1.2 $GtCO_2$ per year in 2035 and 5.2 $GtCO_2$ per year in 2050, with pledges in both years falling below levels in all Paris-compatible scenarios. Announcements by companies sum to over 5 $GtCO_2$ per year in 2050, substantially higher than country pledges. But a multi-$GtCO_2$ gap would remain, and credibility in these announcements is low. Only about one-third of countries mention novel CDR in their mid-century strategies. While conventional CDR plays the strongest near-term role, novel CDR scales up by a factor of five between 2030 and 2035 and accelerates to over $GtCO_2$ per year by 2050 in assessed scenarios. Because emissions have continued to grow since the 2nd Edition, so has the CDR gap. It will continue to widen without significant near-term action to reduce emissions.



5. CDR sits in a broader context of multiple goals and side effects.

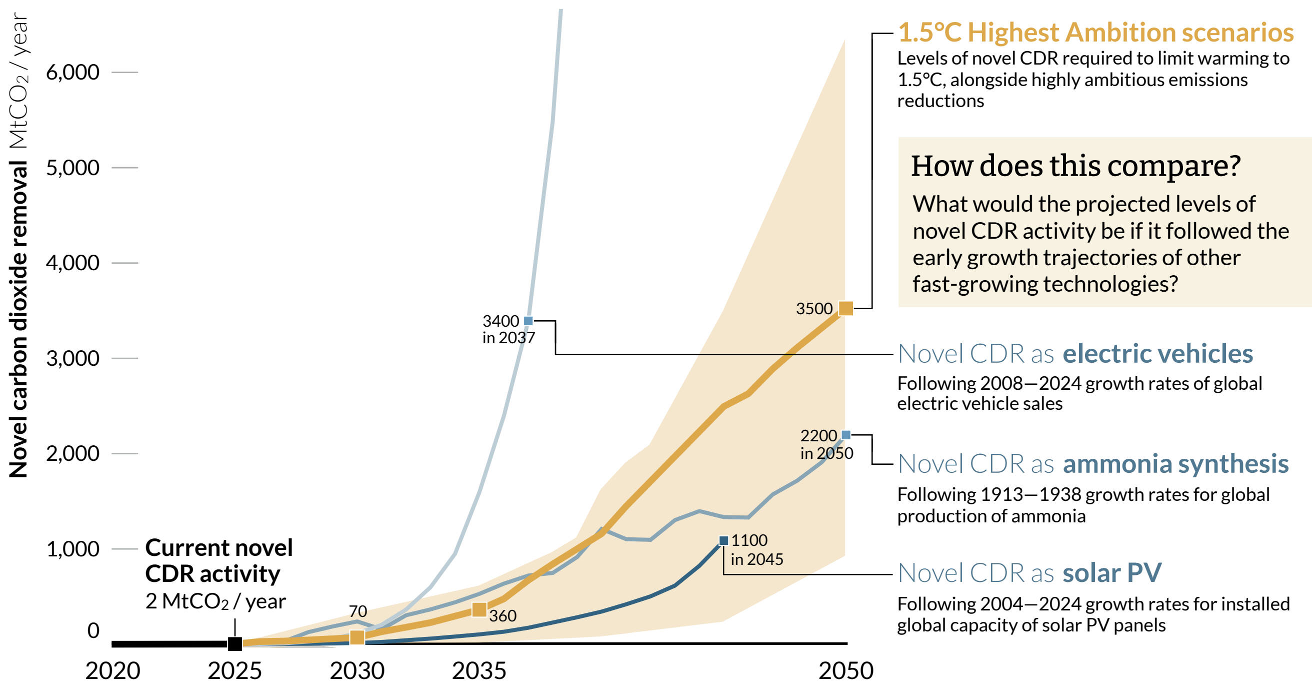
Policies supporting conventional CDR have been implemented for many years and have been motivated by a variety of goals, including ecosystem restoration, biodiversity protection and economic opportunities, as well as stabilizing the climate. Attitudes towards CDR are driven by a wide range of factors including financial payoffs, co-benefits, trust in actors and avoiding harm to ecosystems. Similarly, over half of grant funding for CDR research is for projects described as targeting objectives other than CDR, such as projects focused on wildfires and clean energy. Impacts beyond removing carbon can substantially shape the potential and viability of CDR methods. These side-effects vary by deployment scenarios, typically increase with scale and include consequences for biodiversity, resource consumption, energy use and food production. Some elements of CDR compete with other climate actions (e.g. biomass constraints) while others offer synergies and generate co-benefits. For example, biochar and enhanced weathering can increase crop yields, while durable wood products can avoid the emissions involved in producing similar goods with emissions-intensive processes. Policy design can play an important role in enhancing co-benefits and avoiding harms to produce more sustainable outcomes.

6. Demand for CDR is crucial to closing the CDR gap. While innovative activity has grown, expectations of large and growing demand have become fragile.

R&D, publications, demonstrations, voluntary niche markets and start-up funding in CDR have grown, albeit unsteadily and with some exceptions – particularly high-value patenting, which has declined in recent years. The sustained funding of CDR companies is remarkable given the decline in climate funding overall, of which CDR now accounts for 3%. Last year, contracts for 0.04 $GtCO_2$ of removals were signed in the voluntary carbon market, where purchases from most novel CDR methods come from. Innovation extends to policy innovation with jurisdictions such as the European Union, United Kingdom and Switzerland actively exploring including novel CDR in regulatory schemes. Further, learning by doing is central to innovation, and that depends on expectations of demand, as do other aspects of scale-up. Novel CDR will need to grow at highly ambitious rates, between those seen for solar PV and electric vehicles, which have been the fastest growing climate technologies. Conventional CDR faces different scale-up challenges including competition for land, reversibility, and weakening of the CO_2 fertilization effect as emissions fall. But future demand for CDR has become uncertain. Most policy remains focused on CDR supply, and prices in nascent markets, such as Article 6 of the Paris Agreement and the Carbon Offsetting and Reduction Scheme for International Aviation

(CORSIA), are low compared to the current costs for many methods. Policy dismantling and volatility in the United States are undermining policy credibility and placing pressure on other jurisdictions to adopt policies that will create robust demand and address the CDR gap.

The scaling of novel CDR needed for 1.5°C is very fast but not unprecedented

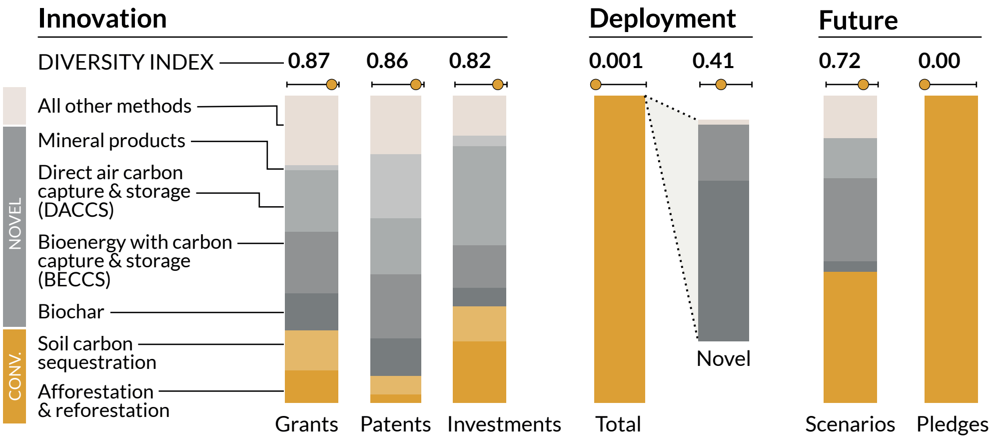


7. Important aspects of the CDR system are highly concentrated, create vulnerabilities, and would benefit from diversification across methods, actors and countries.

Early-stage innovation indicators, such as grants, start-up investments and patents are generally diverse across methods, but later-stage indicators are not. Both CDR deployment and pledges are concentrated in one method (afforestation and reforestation); over two thirds of conventional CDR in voluntary markets is in Latin America; novel CDR is concentrated in two methods (biochar and BECCS); one buyer dominates purchases of novel CDR (Microsoft); most demonstration funding is concentrated in a few countries and projects (Sweden, Denmark and the United States); and start-up investments are focusing on fewer, more mature companies. While first-movers play important roles, if their actions do not diffuse more widely, vulnerability emerges, as evidenced by the impact of US climate policy dismantling and Microsoft's recent adjustments to the pace of its procurement. Further, conventional methods are vulnerable to environmental change and shifting incentives in land use, implying strong benefits to maintaining a diverse portfolio of methods.

A lack of diversity creates vulnerability in the CDR system

Concentration of CDR methods



While indicators of innovation show a high level of diversity across methods, **total deployment and pledges are highly concentrated**

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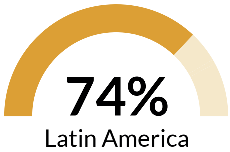
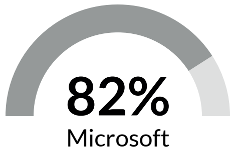
Diversity helps reduce vulnerabilities and enable robust scaling

Concentration of CDR Actors

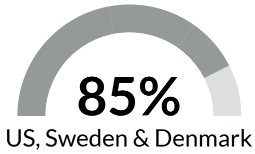
Voluntary Carbon Market
Most conventional CDR credits come from one region



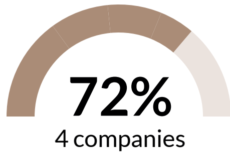
Novel CDR credit buyers
One buyer purchased most novel CDR credits



Announced pilot funding
Most government funding for novel CDR is in 3 countries



Company investments
Most investments across all CDR are in four companies

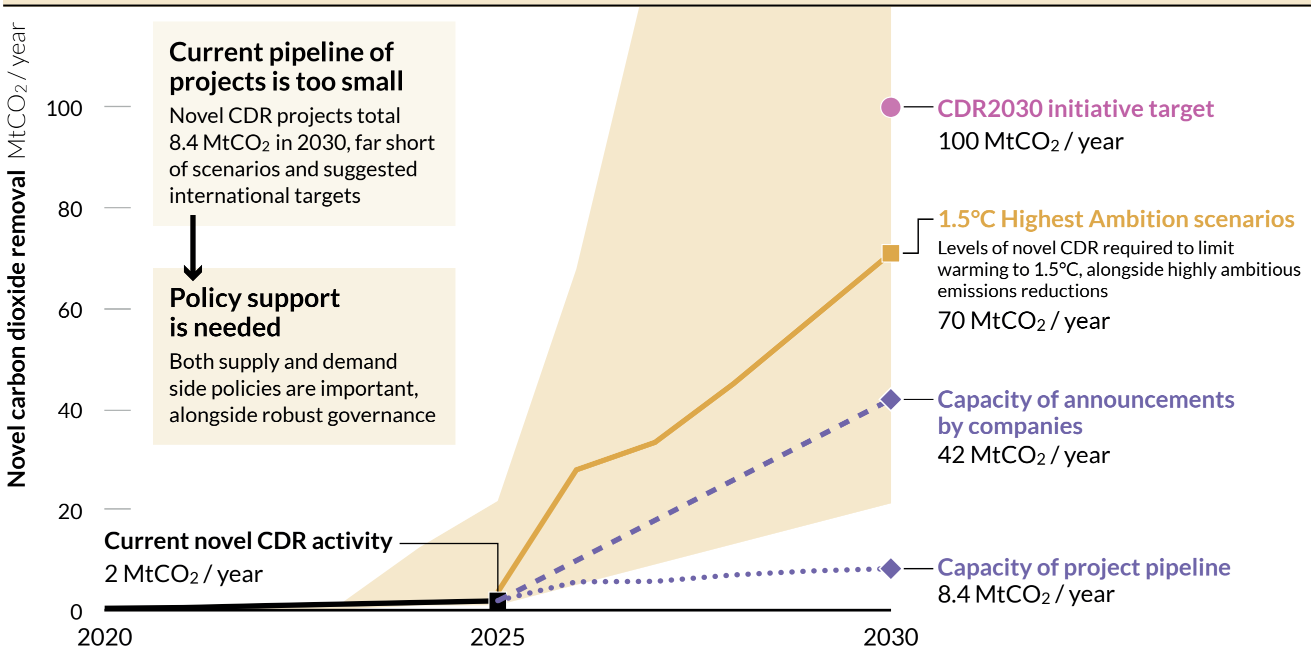


Only **a handful of companies and countries currently drive CDR activity and policy support.**
A loss of one of these major actors could compromise CDR development.

8. Closing the CDR gap is urgent because deployment is a gradual process. The period 2026–2030 is thus critical for establishing CDR's role in limiting climate damages.

Delaying emissions reductions would increase the need to deploy removals, especially novel CDR, if the Paris temperature goal is to be met. A ten-year delay in emissions reductions would raise peak temperature and significantly increase cumulative needs for CDR. Dependence on such high levels of CDR (at the upper ends of potentials) risks crossing sustainability thresholds. Conversely, reducing emissions more rapidly would allow for a more moderate scale-up of removals and reduce sustainability pressures related to land, water, ecosystems and resource demands. Novel CDR is in the formative phase, during which it needs to establish legitimacy, prove reliability and grow sufficiently to make its longer-term contribution to the Paris Agreement goal feasible. While CDR activity is generally growing across indicators, several of them reveal fragile support and dependence on a few critical elements. CDR thus urgently needs to overcome these vulnerabilities and develop a robust policy regime. Benefits of policies need to be clear and extend beyond climate goals. International governance can play a key role in coordinating action and disseminating knowledge about what is effective. Above all, the next five years will require policies to establish strong and growing expectations of demand for removals.

The next 5 years are critical for establishing novel CDR



Chapter 1

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Mangrove replanting, Solomon Islands. By Wade Fairley

Chapter 1 | Introduction

Carbon dioxide removal (CDR) will be necessary to limit climate change, accompanying rapid and deep emissions reductions. This report builds on the previous two editions to track CDR development. It highlights new insights, explores knowledge gaps and defines core concepts while also aiming to improve the reliability and accessibility of CDR data.

Climate change is mainly driven by emissions of carbon dioxide (CO_2) to the atmosphere. These emissions come from human activities such as fossil fuel burning, land-use changes and industrial processes. Emissions of other greenhouse gases (GHGs), such as methane and nitrous oxide, are further exacerbating climate change. Whereas emission reduction seeks to limit the amount of CO_2 newly released to the atmosphere, CDR involves taking previously emitted CO_2 out of the atmosphere.

Meeting the Paris temperature goal – to limit global temperature rise to well below 2°C above pre-industrial levels and pursue efforts to limit the increase to 1.5°C – primarily requires rapid, deep and widespread reductions in emissions. CO_2 emissions have an enduring effect on the climate, causing global temperature to rise and stay elevated for millennia. Halting the rise in global temperature will therefore require bringing emissions of CO_2 all the way down to net zero. Reducing global temperature levels after a peak – for example, to return to 1.5°C after an overshoot period – would require net negative emissions, where global CO_2 removals exceed global CO_2 emissions.

The State of CDR 3rd Edition collates the latest information on the development of CDR. This first chapter sets out the role of CDR in climate change mitigation, defines CDR for the purposes of this report, outlines the characteristics of key CDR methods and presents an overview of the report and key improvements from previous editions.

1.1 Why CDR?

CDR is needed alongside deep and rapid emissions reductions to meet the Paris temperature goal. It should play a smaller role than emissions reductions given uncertainty around the feasible levels of scaling, sustainability limits, storage availability and the risk of reversal, among other constraints. In general, CDR should be seen as a limited resource that will need to be used prudently.

As highlighted in the IPCC's Sixth Assessment Report, CDR can fulfil three major functions.[1-3]

1. In the near term, CDR can help reduce net emissions.
2. In the medium term, CDR can counterbalance residual emissions to achieve net-zero CO_2 or net-zero GHG emissions.
3. In the longer term, CDR can help achieve net-negative emissions – if removals exceed emissions.

Role of CDR in mitigation strategies

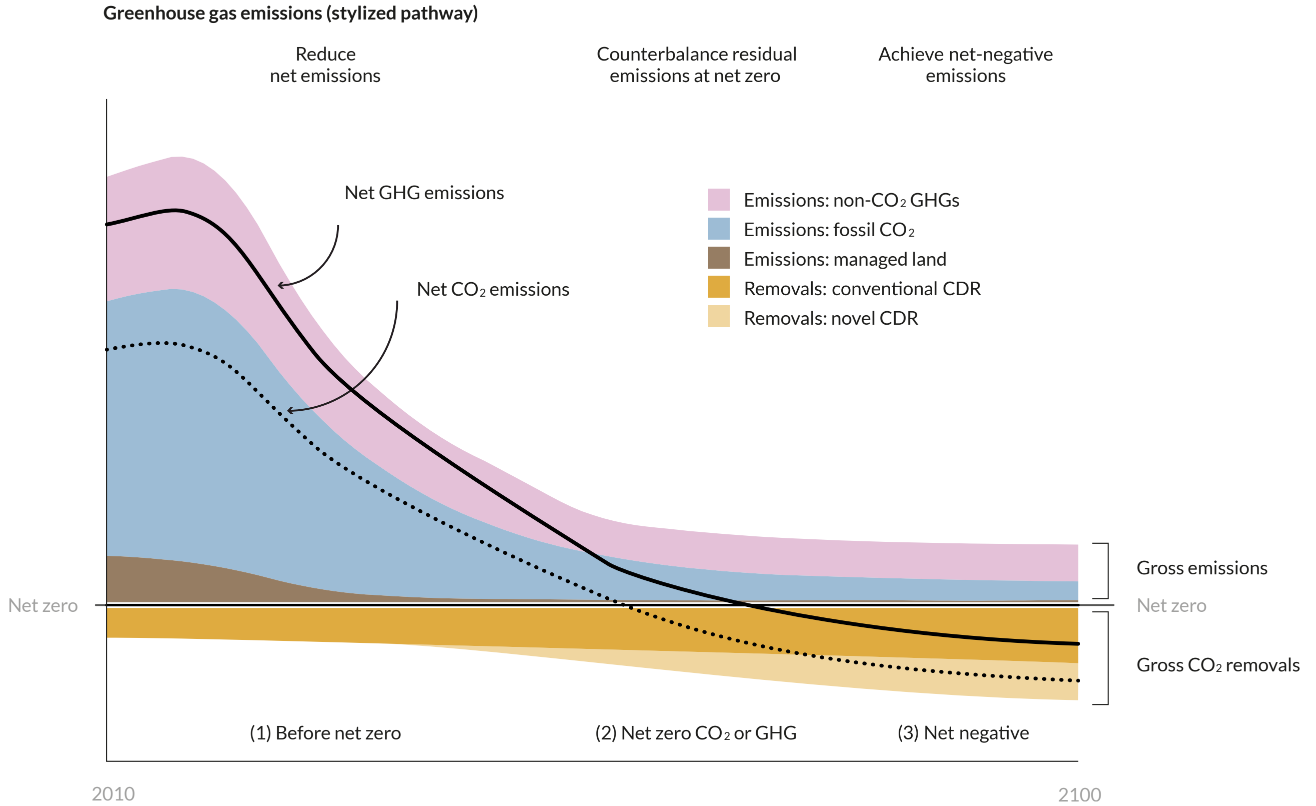

__Figure 1.1__ Roles of CDR in ambitious mitigation strategies, applicable at national and global levels. Shaded areas show basic emission and removal components of mitigation pathways, and lines show the corresponding trajectories for both net CO_2 and GHG emissions. (Adapted from Babiker et al., 2022.)[4]

1.2 Definitions of CDR

This report builds on the definition of CDR used by the IPCC[5]: CDR refers to human activities capturing CO_2 from the atmosphere and storing it durably in geological, terrestrial or ocean reservoirs, or in products. This includes human enhancement of natural removal processes but excludes natural uptake not directly caused by anthropogenic activities.

This definition contains three key principles.

1. The captured CO_2 must come from the atmosphere, not from fossil sources.
2. The subsequent storage must be durable, such that CO_2 is not soon reintroduced to the atmosphere (see Box 1.3).
3. The removal must result from human intervention that is in addition to Earth's natural processes.

Applying the three principles of CDR

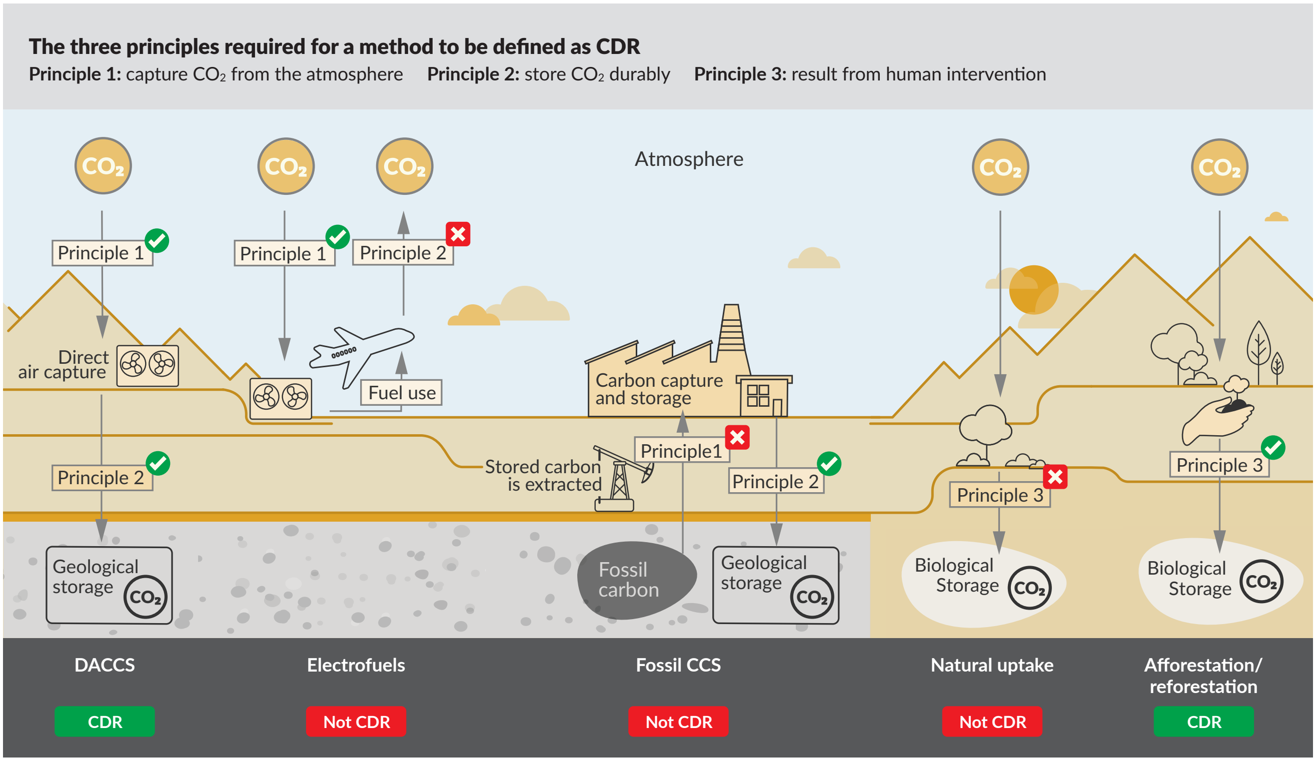

Figure 1.2 *Examples applying the three principles of CDR to different processes. To be defined as CDR, a method must capture CO_2 from the atmosphere (Principle 1) and durably store it (Principle 2) as a result of human intervention (Principle 3). Direct air capture with geological storage (DACCS) satisfies all three principles and is CDR. Several related approaches do not satisfy at least one of the principles and hence are not CDR. For instance, direct air capture of CO_2 for use in short-lived products such as electrofuels does not meet Principle 2. Capture and geological storage from sources of fossil CO_2 does not meet Principle 1. Natural uptake of CO_2 via processes such as tree growth can meet Principles 1 and 2, but they only meet Principle 3 and count as CDR if enhanced through human activity such as afforestation/reforestation.*

It is important to distinguish CDR from other related carbon management terms and concepts, such as carbon capture and utilization (CCU) and carbon capture and storage (CCS). CCU and CCS share components with some methods of CDR, but they do not necessarily result in durable removal of CO_2 from the atmosphere (see Box 1.1).

Box 1.1 Differentiating between CCS, CCU and CDR

CCS is a set of industrial methods for the capture of CO_2, the concentration of this CO_2 into a pure stream and its subsequent geological storage. When the CO_2 comes directly from fossil fuels or minerals (e.g. limestone), this process is an emission reduction rather than CDR. In climate policy and research, the term CCS is sometimes used only for the capture and storage of fossil CO_2 from point sources like coal power plants or cement clinker production. CCS can, however, be applied to CO_2 streams from ambient air, from seawater or the combustion of biomass; in each of these cases, the overall process meets the definition of CDR. This report refers to the first form of CCS as fossil CCS to distinguish it from the usage of CCS in the process chains of some CDR methods, such as direct air carbon capture and storage (DACCS) and bioenergy with carbon capture and storage (BECCS).

CCU is a set of industrial methods for the capture of CO_2 and its conversion into products. Again, CCU methods often use CO_2 from fossil sources, which is not CDR. If the CO_2 comes from the atmosphere and the product is durable (e.g. concrete aggregates and timber for construction), then these CCU applications also meet the definition of CDR. But many CCU products – such as carbonated drinks or fuels – are not durable (and thus not CDR) because they only store carbon for a matter of days or months before it is released back into the atmosphere.

Reporting and accounting perspectives for CDR

The wide-ranging GHG emission and removal effects arising from CDR activities call for robust measurement, reporting and verification (MRV). Policymakers, investors, market operators and the broader public seek trust in the efficacy of CDR methods and the veracity of reporting and accounting activities. Yet, CDR is measured and reported differently in different contexts, which can lead to ambiguity, confusion and inconsistent accounting in assessing progress for CDR within climate targets and strategies. Differences across two key perspectives – national GHG inventories and project-based assessments – reflect differences in objectives, system boundaries and temporal scope (see Table 1.1).

CDR in national inventories

National inventories record emissions and removals from activities within territorial limits during a regular (usually annual) reporting period. Emissions and removals are allocated to the sector in which they occur directly: energy, industry, land use or waste. As an example, removals from reforestation are reported in the land-use sector, while emissions associated with using vehicles to plant and manage the trees are reported separately in the energy sector. If the forest then burns down or is harvested in a later year, the emissions are reported in the inventory for that later year. Since national inventories for the land-use sector are typically based on direct observations, which do not separate natural CO_2 uptake, land-based CDR cannot be fully distinguished in these inventories (see Chapter 7). National inventories do not include emissions that occur in other countries, even if they are associated with imported or exported goods and services (although all emissions and removals are counted, and not double-counted, provided all national inventories are complete). Emissions associated with international shipping and aviation are reported separately. Durability and permanence requirements are not relevant to national inventories because any future reversal of a removal will be reported as an emission in the year it occurs. A nation's climate policy performance can be assessed according to temporal trends in the inventory and comparison to a historical base year. This approach is typically adopted, including in this report, when quantifying national pledges to reduce emissions and scale CDR (see Chapter 9).

CDR in project-based assessments

Project-based measurement seeks to address the question: what is the overall greenhouse gas (GHG) balance of a given project, including upstream and downstream emissions? The approach examines the GHG sources and sinks relevant to a complete CDR activity that, through its various system inputs and outputs, can span sectoral, national and temporal boundaries. In the reforestation example above, the emissions from the vehicles used in planting and management, plus other inputs such as fertilizer, would all be subtracted from the removals generated by the tree growth. This is the approach generally adopted for quantifying CDR credits in voluntary markets (see Chapter 4). While this provides a more complete picture of the climate impact of a project, it may lead to double counting across projects. For instance, emissions reductions from the use of more efficient vehicles could be counted by both the reforestation project and the vehicle manufacturer. Furthermore, there is some degree of choice in setting project boundaries, and assessments can be highly sensitive to this choice. A further sensitivity can come from choosing whether to estimate the absolute balance of GHGs attributable to the project or the GHG balance relative to a counterfactual scenario in which the project does not occur (known as a consequential assessment). Unlike inventories, project-based measurements usually consider permanence or durability, to address requirements from carbon crediting schemes regarding the period for which carbon must be stored and the management of reversal risk.

CDR in mitigation strategies

Quantified scenarios are increasingly used by parties to the UNFCCC, companies, and cities to establish pathways to achieve stated climate pledges, set benchmarks, and identify robust mitigation strategies. While inventory approaches focus on annual fluxes – either positive or negative – and project-based approaches focus on emissions and removals across the lifecycle of a given project, these pathways assess the contribution of a given removal activity to an intended overall climate change mitigation strategy. This is consistent with assessments of the role of CDR in future mitigation trajectories, in which a given activity is included as CDR if it is intended to remove carbon from the atmosphere as opposed to utilizing carbon as part of a broader carbon management strategy (see Box 1.1). This approach excludes, for example, the CO_2 removal that occurs passively as cement recarbonates over the lifetime of a built structure but would include active injection of atmospheric CO_2 to enhance the recarbonation process. It also likely rules out DACCS or BECCS where the captured CO_2 is used for enhanced oil recovery (EOR) due to uncertainties around net positive or negative emission outcomes (see Box 1.2). Policy documents, such as nationally determined contributions (NDCs), increasingly reflect these strategies by making explicit the role of CDR and the specific approaches that will be used to achieve climate targets.

Three approaches to CDR accounting and reporting

	Objective and governance context	System boundaries	Temporal scope
National inventories	To report total GHG emissions and removals categorized by sectors of activity in a given period	Emissions and removals occurring within national borders, allocated to the sector in which they occur directly	Emissions and removals reported as a time series (usually annual)
Project-based assessments	To measure the overall GHG balance of a complete project	Emissions and removals pertaining to the project lifecycle, across sectors and national borders	Emissions and removals integrated over the project's entire lifecycle
Mitigation strategies	To plan for CDR activities as part of a portfolio of measures to meet an emissions target or climate objective	Emissions and removals as part of a mitigation strategy (system boundaries generally wider than inventories but narrower than lifecycle assessments)	Emissions and removals integrated over the whole span of the planned activity for each method

Table 1.1

Gaps and grey areas

Several barriers impede the ability to make connections across CDR perspectives. The way in which some emissions and removals are measured and reported can differ greatly between the project level and the national inventory level. Project-level carbon credits are also being issued for CDR methods that currently lack approved inventory guidance, hampering the capacity of countries to report and account for them. This is particularly the case for several novel CDR methods including enhanced weathering (EW) and mineral products. The IPCC Task Force on National Greenhouse Gas Inventories has been tasked to provide a methodology report on CDR, CCS and CCU by the end of 2027. This is expected to lead to additional guidance on how to report removals for methods in national GHG inventories under the United Nations Framework Convention on Climate Change (UNFCCC).

Despite the obstacles, efficient scaling of CDR will involve MRV activities connecting and interacting at the project, national and organizational levels. Policies and measures designed by countries to incentivize CDR projects will be effective if, in turn, they create measurable signals in the national GHG inventory that allow such interventions to count towards national and international targets. Similarly, voluntary investments in CDR projects have greater legitimacy if the measured emissions and removals follow accepted international MRV standards and support alignment with national GHG inventories. Work is ongoing to address at least some of these gaps, although others face more significant challenges, such as improving the accuracy and spatial resolution of land monitoring methods.

Box 1.2 CDR grey areas

Depending on which approach is taken and how the IPCC's CDR definition is interpreted (e.g. what constitutes human activity), what counts as CDR can be contested. Not surprisingly for an emerging field, "grey areas" exist where delineations are not straightforward. Examples relevant for this report include the use of CO_2 from the atmosphere for EOR, the status of cement recarbonation and removals on abandoned agricultural land (see Chapter 7).

EOR with CO_2 from BECCS or DACCS. In this approach, non-fossil CO_2 is captured and injected into depleted oil reservoirs to increase oil recovery. Carbon that is captured and stored through this approach would be reported in a national inventory as removal, and the carbon released to the atmosphere from later combustion of the oil would be counted as an emission (where and when it occurs). A project-based accounting perspective would estimate the net effect of removals and emissions, which current estimates suggest would most likely lead to net emissions.[6] It is therefore ambiguous and case-specific whether EOR with non-fossil CO_2 could be considered an approach to either reduce emissions (similar to CCU approaches) or actively remove carbon from the atmosphere. Because of this, we choose not to include it in our estimates of CDR. BECCS and DACCS with EOR may still play a role in supporting innovation in the underlying technologies for future deployment in contexts that would count as CDR (i.e. without EOR).

Cement recarbonation. Cement production contributed around 4% of global emissions in 2023, primarily from limestone calcination. Over a building's lifetime, a proportion of the emitted CO_2 is reabsorbed via cement carbonation. We consider cement recarbonation not to be a direct human intervention but instead an indirect effect that depends on local climate conditions. Consequently, it is not included in our summary estimates of CDR – although it is a sink that contributes to counterbalancing human emissions. Furthermore, we do include approaches that directly enhance recarbonation as CDR in the "mineral products" category.

Abandoned agricultural land. We include forest regrowth on abandoned agricultural land in our summary estimates of CDR, despite debate over whether it constitutes direct human intervention. In some cases, land that was used for agriculture may be returned to forest through active tree planting, which is clearly CDR. In many cases, however, the forest cover may regrow without any direct human intervention, and agriculture is often abandoned for reasons other than CDR. This abandonment is less clearly a human activity, but even in these cases it could be argued that the continued non-use of the land reflects a human decision. Given this argument and a lack of data to distinguish between the different drivers and interventions in each case, we include all forest growth on abandoned agricultural land in the "afforestation, reforestation and forest management" category.

1.3 CDR methods and their characteristics

There are many CDR methods, covering a variety of ways to capture and store CO_2. Each CDR method can be thought of as a particular route through the Earth's carbon cycle – capturing carbon from the atmosphere and transferring it to durable carbon pools. Each of these pools is characterized by a different carbon storage timescale. CDR methods also differ in their readiness for scaling and their biophysical or technical sequestration potential (see Figure 1.3).

Routes through the carbon cycle

CDR methods use a range of capture processes and storage pools. Between capture and ultimate storage, carbon may be converted and transferred through a number of these carbon pools. Some methods involve transfers of carbon through multiple steps – and potentially over multiple years – while others combine capture and storage in a single step.

CO_2 sinks

Processes that capture CO_2 from the atmosphere are referred to as sinks.

Biological capture. Through the process of photosynthesis, CO_2 is taken up from the atmosphere and converted into biomass. On land, this capture occurs in vegetation including trees and agricultural crops. It also occurs in aquatic habitats, such as mangrove or kelp forests and seagrass meadows.

Chemical capture. A range of non-biological natural and industrial chemical processes can also capture CO_2. Some of these processes already occur as part of the Earth's natural carbon cycle. Through weathering, for example, certain minerals react with atmospheric CO_2 to produce either solid carbonate minerals or, in the ocean, dissolved bicarbonate. Other processes involve chemicals from human industrial activity. These can be alkaline wastes – for instance, from cement and steel production – or solvents and sorbents designed specifically to capture CO_2 and then rerelease it as a concentrated stream for use or storage.

Carbon pools

Vegetation, soils and sediments. Carbon can be stored in several ways on land. Although non-woody vegetation typically does not sequester the carbon captured in its biomass for long, individual trees can retain the carbon they capture for many decades, and forest ecosystems can retain carbon for centuries. Soils and sediments contain carbon in several forms, including organic carbon compounds from the residues of vegetation, animals and microbes, and inorganic carbon from weathered rocks. Human interventions can enhance the amount and durability of carbon on land, such as when biochar is applied to soils.

Marine inorganic and organic carbon. In the ocean, carbon is stored primarily as bicarbonate and carbonate ions, the dominant forms of dissolved inorganic carbon. The ocean also stores carbon in organic matter, including in sediments on the floor of the deep ocean that can sequester carbon on long timescales. Organic carbon is deposited onto these sediments as the remains of plants and animals that sink to the seabed.

Geological formations. Concentrated CO_2 streams generated from chemical capture can be injected into formations such as depleted oil and gas fields, saline aquifers or reactive mineral deposits underground. Various processes then act to sequester the CO_2 in these formations, including physical trapping by impermeable rocks, dissolving of the CO_2 in water and eventual mineralization.

Minerals. Solid carbonate minerals such as calcite ($CaCO_3$) are generated directly by some processes of geochemical capture, such as weathering or reaction with alkaline materials.

Built environment. Several products used in the construction of the built environment are durable stores of carbon. For example, timber has been used widely as a construction material for centuries and contains the carbon captured from the atmosphere by trees. Solid carbonate minerals generated through capture of CO_2 from the atmosphere can be used in products such as aggregates, asphalt, cement and concrete.

Durability

In this report, CDR methods are defined as sufficiently durable if the carbon pool has a characteristic storage timescale on the order of decades or more. However, this approach to what counts as CDR is not definitive. Policymakers and scientists have yet to agree on a clear definition of durable carbon storage (see Box 1.3), and expert interpretations are expected to evolve as research continues.

Different carbon pools have very different characteristic timescales for carbon storage and different risks of reversal (i.e. of rereleasing the carbon). Well-chosen geological and mineral formations offer the longest and least reversible storage. However, many other storage methods are widely regarded as valid for CDR, such as storage in trees and soils.

Box 1.3 Defining durable storage

The temperature-raising effect of fossil CO_2 emissions lasts for millennia[7] – an important consideration in any effort to balance emissions and removals. Any storage for shorter than this very long timescale will not fully counteract warming due to fossil CO_2 emissions. Maintaining net-zero CO_2 emissions – and hence halting global temperature rise – requires any residual emissions of fossil carbon to be balanced by capturing carbon from the atmosphere and storing it on the same millennial timescale.[8]

Some scientists argue that efforts to neutralize remaining fossil CO_2 emissions with CDR methods that have durabilities lower than 1,000 years are insufficient.[8,9] Storage in geological formations and through mineralization have the longest characteristic timescales. They are also the least susceptible to releasing CO_2 into the atmosphere as a result of human and natural disturbances once storage has occurred. Storage in geologic formations does carry risk of release – particularly during injection. However, in terms of like-for-like durability, it offers the closest equivalence to emissions of fossil CO_2 if selected and operated well.

Other scientists argue that there are sustainability and climate benefits to pursuing a portfolio of removal approaches with different durabilities.[8,10,11] Shorter-term storage can have value in meeting net emissions reduction targets, and counterbalancing biological CO_2 or methane emissions might also imply different durability requirements.[12] It is widely agreed that CDR does not encompass products that rerelease carbon within a year (e.g. direct air capture to fuels, or biomass to food). But there is currently neither a clear scientific basis nor a consensus among policymakers for incorporating a storage durability threshold in the definition of CDR.

Existing policies by governments and voluntary standard setters have various minimum thresholds regarding storage.[13] Of 27 standards with an identified duration, over half require between 10 and 50 years, yet the single most common threshold – held by nine standards – is 100 years.[14] The EU's Carbon Removals and Carbon Farming Regulation (CRCF) has defined the concept of "permanent carbon removal" as storage for "several centuries", and a similar threshold of 200 years is a condition for the integration of CDR credits into the UK Emissions Trading Scheme (UK ETS).

The State of CDR assessments define durability based on the characteristic storage timescale of the relevant carbon pool. A method is counted as CDR if this timescale is on the order of decades or more. Figure 1.3 shows the characteristic storage timescales for different CDR methods. But the actual duration of storage depends not only on the general characteristics of the pool but also on human factors. For example, storage in soils could be reversed by a change in land use or extended through careful maintenance.

Categorizing CDR methods

The variety of processes for capturing and converting CO_2, and of options for its storage, means there are many potential methods of CDR. Figure 1.3 provides an overview of the key CDR methods considered in this report. While not exhaustive, this list is composed largely of methods that are already being deployed and those already analysed in the research literature. This report broadly follows the categorization and naming of methods used in the most recent IPCC assessment.[4] Whenever a specific CDR method is referred to in this report, the associated definitions and characteristics shown in Figure 1.3 apply. More detailed descriptions of these CDR methods can be found in the Glossary.

Characteristics of CDR methods

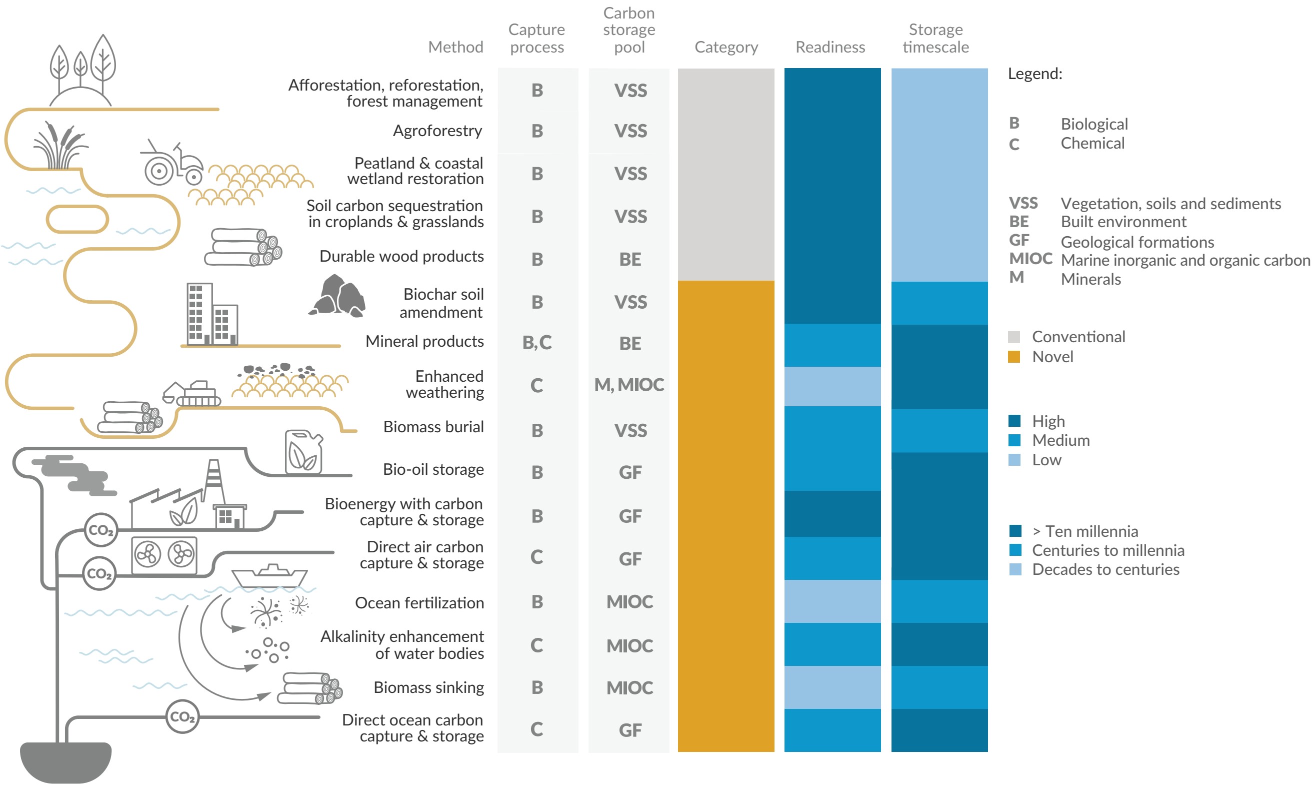

Figure 1.3 *Summary of CDR methods, noting their respective capture process and storage carbon pool, categorizations as "conventional" or "novel", readiness, and characteristic storage timescale. Mineral products here include aggregates, asphalt, cement and concrete as well as biogenic* CO_2 *from BECCS or biochar applied in building materials. (Based on Babiker et al. 2022, Bustamante et al. 2023, and Cobo et al. 2023; see Chapter 10 for further discussion on readiness of different CDR methods.)*[4,15,16]

In policy debates and the media, CDR methods are often grouped into categories for ease of reference. A distinction is commonly made between "natural" or "nature-based" methods and "technological" or "engineered" methods. This categorization is contested, however, as well as blurred (a third "hybrid" category is also frequently employed). There are a variety of ways in which CDR methods could be grouped, and there is as yet no universal agreement on classification. The rows in Figure 1.3 indicate characteristics that are useful to consider when categorizing CDR methods in different contexts, including in different parts of this report.

This report refers to individual methods where possible, or groups them by common measurable properties where necessary. As in the 2nd Edition, this assessment also continues to distinguish between two broad categories: conventional CDR and novel CDR. This categorization is based on a combination of two of the methods' characteristics: their current level of readiness for deployment and the characteristic timescale of the carbon storage they employ.

Conventional CDR. This category encompasses CDR methods that are well established, already deployed at scale and widely reported by countries as part of LULUFC activities. The methods included in this group are afforestation, reforestation and forest management; agroforestry; soil carbon sequestration in croplands and grasslands; peatland and coastal wetland restoration; and durable wood products.

Novel CDR. This category encompasses all other CDR methods. These methods generally have a longer characteristic storage timescale and lower level of readiness for deployment and, as a consequence, are currently deployed at smaller scales (see Chapter 7). Examples of such methods include BECCS, DACCS, biochar soil amendment, mineral products, biomass burial, direct ocean carbon capture and storage (DOCCS), and alkalinity enhancement of water bodies.

1.4 Purpose and scope of this report

Interest in CDR as a necessary component of climate action continues to intensify among policymakers, investors, researchers and non-profit organizations. Experience with – and information about – CDR also continues to grow, including research and development, demonstration projects, purchases of removal credits, and recommendations for best practices from public and private sector organizations. CDR requires strong policies and governance to support the development and deployment of a diverse range of methods and ensure that projects are implemented responsibly. However, recent analysis (published in our first *Insight Report*) reveals that transparency around CDR commitments in national climate pledges remains limited, with only a handful of countries providing clear information on their intention to scale CDR.

While a scale-up of CDR will be needed to address future climate change, the appropriate level of CDR deployment remains uncertain. This report estimates future CDR needs based on the best available science, but there are significant uncertainties in both future emissions and the climate response to emissions and removals. It is also uncertain how effective CDR approaches will be in a changing climate. We may need far more CDR than currently envisioned to reach temperature stabilization or reverse warming after surpassing 1.5°C. This underscores the potential need to build capacity for large-scale deployment – and the value of deploying CDR proactively now as a hedge against future climate uncertainties. This deployment will involve concerted effort across many dimensions, and tracking this effort requires a resource for reliable, transparent and up-to-date data.

The State of CDR aims to meet this need. The 1st Edition, released in January 2023, provided a comprehensive global assessment of developments in CDR. The aim of the report was to inform and guide the further development of CDR by providing a clear, independent and authoritative assessment of available data. The 2nd Edition, released in 2024, expanded the scope and depth of the assessment. It introduced a model based on theories of innovation to provide a more coherent picture of CDR development, tracking the progression from research and development through demonstration, upscaling and market growth. The 2nd Edition also broadened coverage by introducing new chapters on demonstration and upscaling, the voluntary carbon market, and MRV. It expanded the author team and improved methodologies for estimating current CDR levels and assessing future requirements.

Interest in CDR continues to accelerate. The response to the first two editions highlighted the demand for regular tracking of the rapidly evolving CDR landscape. This 3rd Edition continues and expands the assessment of CDR development. In the next three chapters, the report assesses the state of CDR in terms of research and development (Chapter 2), demonstration and upscaling (Chapter 3) and voluntary demand for CDR (Chapter 4). It then examines enacted policy approaches and commitments by governments to develop CDR (Chapter 5) and reviews how communication and public perceptions are evolving (Chapter 6). The report's final chapters look at the amount of CDR currently being deployed (Chapter 7), the amount required by pathways that meet the Paris temperature goal (Chapter 8), and the gap between government proposals and pathways to the Paris goal (Chapter 9). A new chapter assesses current evidence on the costs and potentials of CDR methods (Chapter 10).

Beyond the new chapter on costs and potentials, the 3rd Edition introduces several key advances and benefits from new analyses and data collection efforts. These include a survey on the pipeline of CDR projects and future company ambitions, and new integrated assessment model scenarios submitted by modelling teams for global and national models. This edition also includes an expanded set of indicators and a revised data portal, freely available via https://www.stateofcdr.org/data-portal/3rd-edition. Despite these enhancements, important gaps remain. Most importantly, increased data transparency and dedicated data gathering efforts focused on activities outside Europe and North America are needed to provide a fuller picture of the state of CDR.

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Chapter 2

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Scientist collecting a sediment core to assess carbon sequestration rates in a tidal seagrass bed. By Jeff Hester

Chapter 2 | Research and development

Funding for research and development (R&D) has been increasing steadily. R&D remains concentrated in a few countries and on a few CDR methods, although signs of diversification are emerging. While the number of scientific publications continues to grow, patenting activity has been gradually declining. Across the CDR sector, consistent signals of a significant acceleration in R&D activities have yet to emerge – particularly at the interface with commercialization.

Key insights

- Although the number of CDR research grants is declining, total funding is increasing due to a shift towards larger, higher-value projects. This structural shift has driven funding growth of approximately 13% per year between 2022 and 2025.

- Targeted CDR funding is rising, but most CDR publications continue to emerge from research supported by grants that are not explicitly focused on CDR, highlighting the continued importance of broader R&D programmes in enabling CDR research.

- The CDR literature continues to grow, with the overall number of publications increasing 15% per year on average between 2022 and 2025. Publication growth is strongest for ocean alkalinity enhancement (an average annual increase of 43% between 2022 and 2025) and DACCS (28%), while scientific publications on biochar (13%) forest-based methods (9%) and BECCS (6%) are growing more slowly. Innovation in CDR as measured by patenting has declined (an average annual decline of 4.0% between 2011 and 2019); this contrasts with slight growth in overall climate change mitigation patenting (average annual growth of 2.2% between 2011 and 2019). This downward trend in CDR patenting is partly driven by a significant reduction in patenting in BECCS.

- Some CDR methods reviewed for the first time in this edition – such as biomass burial and sinking, mineral and wood products, and ocean capture – receive little funding and generate few publications compared with other CDR methods. However, mineral products are a significant focus of CDR innovation, accounting for 14%–30% of annual patenting activity between 2005 and 2022.

- Knowledge about research activity, funding and patenting across CDR methods – combined with insights on their potential, costs and socioeconomic and geographic contexts – can help inform decisions about public funding for R&D and the early deployment of novel CDR.

Staying within the temperature goal of the Paris Agreement will require an unprecedented acceleration of innovation and scale up across low-carbon, carbon-neutral and carbon-negative, or CDR, technologies. While sustained innovation is essential over the long term to enable the deployment of CDR at climate-relevant scales, it is equally critical in the near term to support the development of a diverse portfolio of complementary CDR methods. Such diversity supports tailored deployment strategies subject to different geographic and ecological contexts as well as policy preferences. Diverse CDR portfolios also help hedge against the risks associated with overreliance on any single technology during technology development and scale-up.

Assessing the state of innovation in CDR is therefore vital. It enables a clearer understanding of how different CDR methods are developing, the pace at which they could be scaled, how their costs may evolve, and which risks and benefits are associated with them. Because innovation is a process that involves how technologies are conceived, developed and deployed, a diverse set of metrics is needed to assess its evolution.[1] At the same time, the innovation process should not be understood as a linear progression. Rather, it is a dynamic and iterative process in which different stages in the innovation chain are interconnected and often occur concurrently. Furthermore, feedback loops between research, development, demonstration and deployment phases play critical roles in shaping technology outcomes.

R&D activities, together with their associated outputs, are widely examined to understand the early stages of the innovation process. These activities encompass the discovery and assimilation of new scientific and technical knowledge and range from fundamental research to applied technology development and small-scale demonstration projects that precede broader commercialization and large-scale deployment (see Chapter 3). Developing a comprehensive understanding of the evolution of R&D in the CDR sector requires integrating insights across this full spectrum of activities and outputs. However, limitations in data availability constrain the ability to capture all aspects of R&D in a comprehensive manner. As a result, available indicators provide only a partial, albeit informative, representation of innovation dynamics within the CDR sector.

This chapter assesses the state of R&D in CDR using three complementary indicators.

1. Research grants serve as an input-related metric, capturing early-stage investments in R&D. This data provides insight into the level of effort dedicated to advancing CDR methods, including activities aimed at improving scientific understanding, evaluating risks and co-benefits and reducing costs.

2. Scientific publications are used as an output-oriented indicator of R&D activity. They reflect the generation and dissemination of new knowledge and provide a basis for assessing the evolution of the CDR knowledge base.

3. Patenting constitutes an additional output-oriented indicator of inventive activity, capturing the extent to which R&D efforts are moving technologies closer to commercialization.[2]

The State of CDR 3rd Edition provides updated estimates for each of these indicators, incorporating significant methodological improvements in the compilation and evaluation of the underlying data compared to previous editions. In addition, the chapter explores some of the linkages between indicators, for example by analysing research grants linked to CDR publications.

2.1 Funding of R&D

Overview of research grants explicitly focused on CDR

Funding for R&D is a fundamental entry point for accelerating innovation in CDR. Yet, available data is limited, making it difficult to assess the development of funding for R&D activities globally and comprehensively. Public funding through grants can be used to steer R&D and stimulate knowledge creation in specific areas.[3] Grant data thus provides an input-based indicator of efforts to expand knowledge on CDR through basic and applied research at public universities and research facilities, sometimes in cooperation with private companies.[4,5] For this report, we use data from the Dimensions database, which provides global coverage of public and private project-specific funding through R&D grants. We leverage comprehensive search queries to identify potentially relevant grants and use machine-learning classification to determine whether they are discussing CDR and if so, which CDR methods they are covering. The Technical Annex and Mueller-Hansen et al. (2025)[6] provide further details on the database, its coverage and the methods applied to identify grants on CDR. While this does not provide the full picture of CDR R&D activities, as it does not cover base funding of universities and research institutes or privately funded research activities on CDR, it nevertheless gives some indication of recent developments at this early innovation stage.

Our analysis finds about 7,300 CDR research grants that started in the 21-year period from 2005 to 2025, covering different CDR methods to various degrees. About 1,400 (20%) of those started within the last three years (between 2023 and 2025). In total, we estimate a funding volume for these grants of US$5.6 billion (10th–90th percentile range: US$3.9 billion to US$6.4 billion), of which US$1.9 billion (34%) falls within the last three years, which *The State of CDR 2nd Edition* did not cover. The 3rd Edition also compares research grants awarded to CDR to those awarded to a diverse set of low-carbon technologies, including renewable energy and carbon management technologies.[6] We estimate that CDR research grants represent 4.4% of all low-carbon technology grants awarded between 2005 and 2025 and 3.3% of total funding volumes. While funding for low-carbon technology grants saw an average growth rate of 12% per year between 2005 and 2025, funding for CDR grew by 15% per year over the same period.

Recent trends emerging from our data on R&D grants present a mixed picture, with declining total numbers of grants but increases in funding amounts. The number of active research grants declined by 1% between 2023 and 2024 (see Figure 1a), while the number of new grants dropped by 32% over the same period. (Data for 2025 is likely incomplete due to reporting lags.) The trends are different across CDR methods: while there is a stronger decline in active research grants for biochar soil amendment and afforestation, reforestation and forest management, the following methods experienced increases: direct ocean capture, mineral products, alkalinity enhancement of water bodies and ocean fertilization. The remaining methods stayed relatively stable.

The total amount of funding for CDR offers a different picture: average funding per project increases over time, resulting in higher total funding despite the decline in project numbers. The mean funding amounts of projects that started between 2023 and 2025 are almost double those for projects that began between 2005 and 2022. Despite the decrease in the total number of grants, funding has grown between 2023 and 2025 at 13% per year. This is similar to the funding growth over the full period covered by the data (15%) and is broadly in line with the 15% growth in CDR publication output (see Section 2.2).

Funding patterns show a concentration on specific CDR methods (see Figure 2.1b). Soil carbon sequestration comprises the largest share (24%) of active grants between 2023 and 2025, followed by biochar (18%) and afforestation, reforestation and forest management (14%). While DACCS (11%) and BECCS (4%) only make up small percentages of active grants, they get much higher shares of the funding amounts (22% and 17%, respectively) due to substantially larger project sizes.

Grant funding for CDR is concentrated in Europe and North America. Between 2005 and 2022, 53% of funding originated in North America, 32% in Europe and only 15% in all other regions combined, measured by the number of years that grants were funded in the respective regions. For the period between 2023 and 2025, which was added for the 3rd Edition, the figures are 39% for North America, 44% for Europe and 17% for all other regions combined. In terms of funding amounts, the largest shares between 2005 and 2022 came from North America with 48% and Europe with 43%. Between 2023 and 2025, Europe took the lead with 63%, followed by North America with 35%. While our data for 2023 to 2025 for China, South Africa and Russia has gaps, the larger pattern of a strong concentration of funding in Europe and North America remains valid. European and North American grants tend to focus more on novel CDR (except biochar), while grants in other regions have higher shares of conventional CDR and biochar. For example, grants awarded by funders from Asia have a high share of peatland and coastal wetland restoration research (see Figure 2.1c).

Other research grants leading to CDR publications

In addition to research grants that explicitly mention CDR in their high-level summaries (title and abstract), this edition of *The State of CDR* introduces a new indicator – grants co-funding CDR research (hereafter "co-funding grants"). This indicator tracks the number and funding volume of grants that are acknowledged in CDR publications but not classified as CDR-specific by our machine-learning approach (see Technical Annex A.2.1). As such, the indicator provides insight into the extent to which CDR research draws on or contributes to a broader portfolio of funded projects in which CDR is not the focus. For example, a grant focused on forest fires and their impacts on vegetation and soils may result in a CDR-relevant publication assessing drought-resistant tree species and their carbon storage potential. Similarly, a materials engineering grant developing next-generation membranes for fuel cells and electrolyzers may co-fund research that leads to a publication on membrane development for DACCS.

We find that there has been substantial acknowledgement of co-funding grants within the CDR literature. Using the Dimensions database, we built a dataset of 18,238 CDR publications issued between 2005 and 2025 that contain supporting grant information. Of the 14,573 unique grants acknowledged across those publications, approximately 11,000 are not classified as CDR-related based on their high-level summary. (Note, however, that CDR could be mentioned in the full text of grant applications, which are not publicly accessible.) Co-funding grants thus support a substantial portion of CDR research activity; a majority of publications (56%) acknowledge only co-funding grants, while just 27% are funded solely by research grants that explicitly mention CDR. The remainder acknowledge both CDR grants and co-funding grants (17%).

Research support from co-funding grants – measured in terms of grant acknowledgements in CDR publications – appears to have been consistently high over time for both conventional and novel CDR methods (see Figure 2.2). For conventional CDR methods, the share of co-funding grants in total grant acknowledgements has remained relatively stable at around two-thirds between 2005 and 2025. For novel methods, this share was higher in the early 2000s but has decreased substantially since then and is now on par with the share for conventional methods.

Overview of R&D grants, 2005–2025

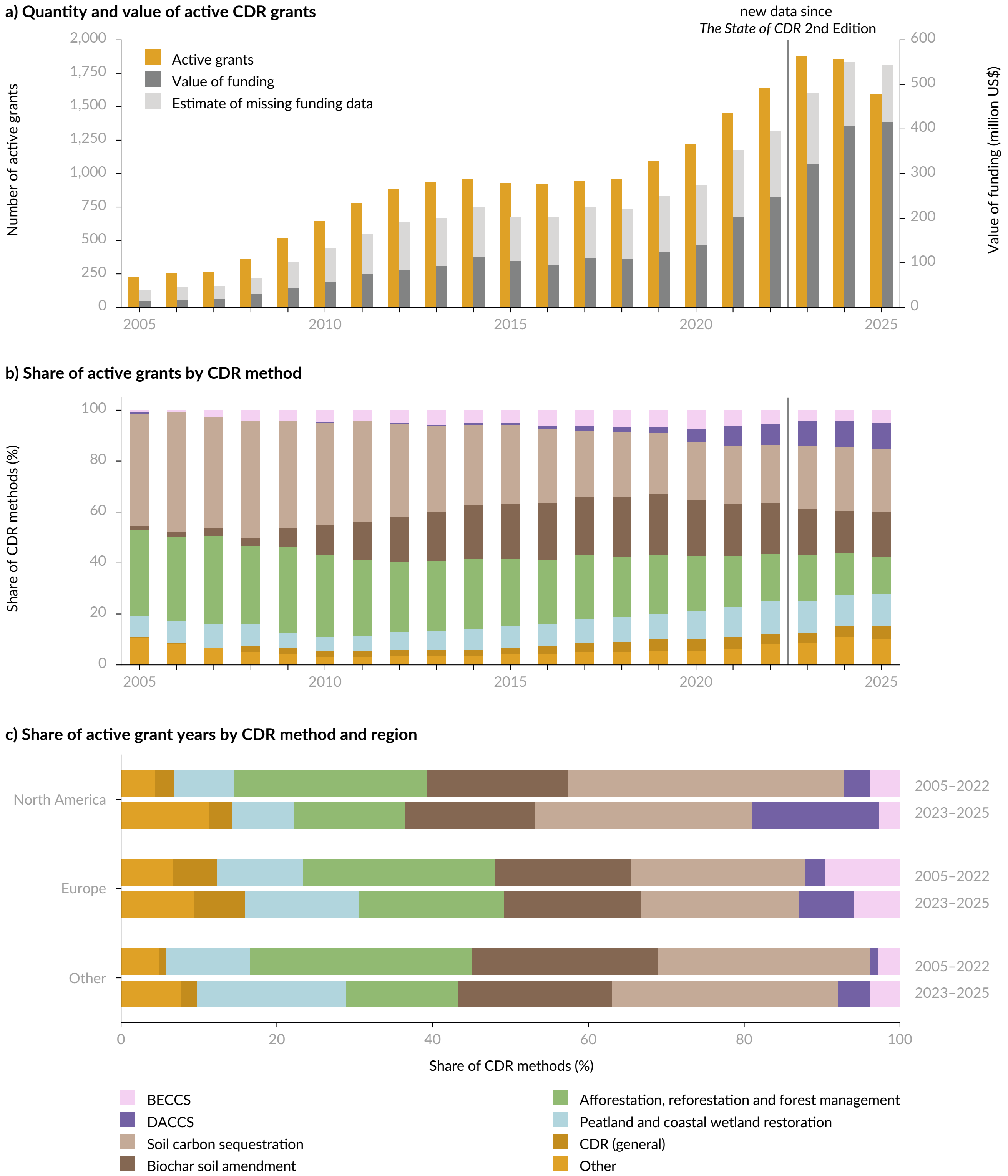


Figure 2.1 *(a) Active grants (left-hand axis) and funding over time (right-hand axis), (b) shares of CDR methods in active grants per year, and (c) regional shares in active grant years for early data versus new data. In panels (b) and (c), the "other" category includes the following CDR methods: enhanced weathering, ocean fertilization, mineral products, ocean alkalinity, durable wood products, direct ocean capture, agroforestry, biomass sinking and bio-oil storage. As data from the main Chinese funder was not available from 2022 onward, we also excluded earlier Chinese data from display so that data sources are consistent over time. Data from 2025 may be incomplete because of reporting lags.*

Number and share of co-funding grant acknowledgements, 2005–2025

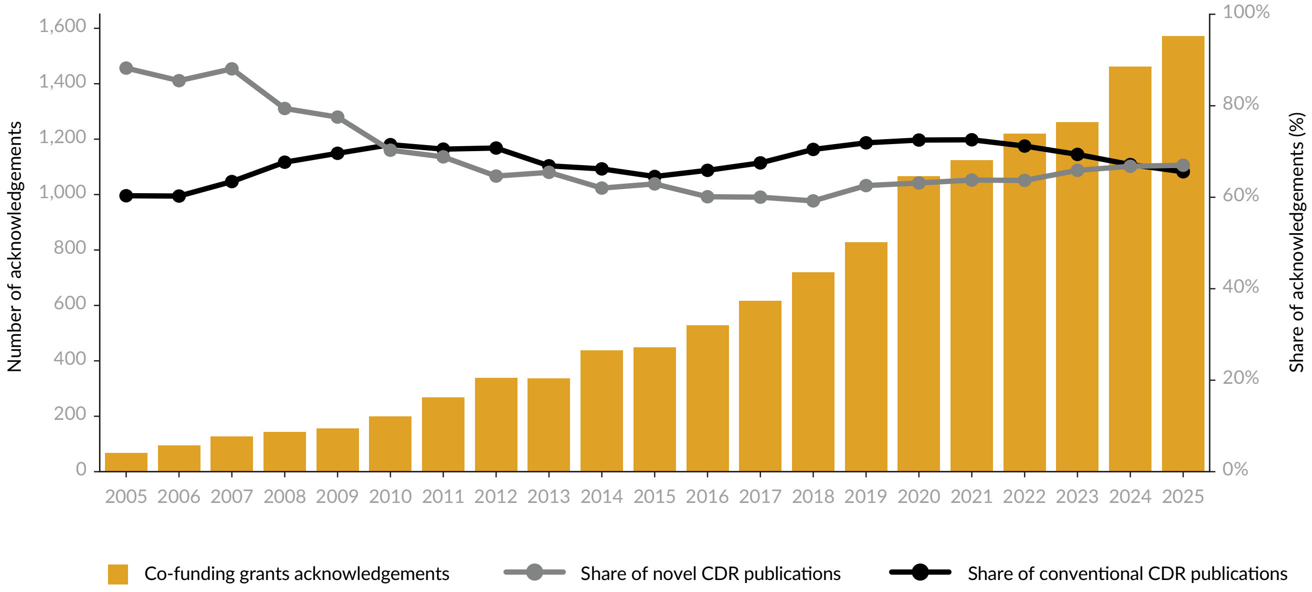


Figure 2.2 *Co-funding grant acknowledgements for CDR publications. Lines show three-year moving averages of the shares for novel and conventional CDR publications. As data from the main Chinese funder was not available from 2022 onward, we also excluded earlier Chinese data from display so that data sources are consistent over time. Data from 2025 may be incomplete because of reporting lags.*

In terms of specific CDR methods supported by co-funding grants, the pattern is similar to that observed for targeted CDR grants. About 35% of co-funding grants in our database are acknowledged by publications on biochar soil amendment or soil carbon sequestration, respectively. Moreover, 30% of co-funding grants are mentioned or acknowledged in publications on afforestation, reforestation and forest management. By contrast, novel methods such as BECCS (5%) and DACCS (4%) are associated with only a small share of co-funding grants.

About 83% of acknowledged co-funding grants include a reported funding amount. As a rough proxy for the portion of funding dedicated to CDR research, we weight each grant's total funding by the share of CDR publications among all publications citing that grant. This results in roughly US$2.5 billion in CDR-attributed funding. After imputing missing funding data for the remaining 17% of grants, the total estimated funding for CDR research from acknowledged co-funding grants rises to approximately US$2.7 billion (10th–90th percentile range: US$2.6 billion–US$5.2 billion). Together with the results for CDR-specific grants, we estimate a total CDR R&D funding volume through grants of around US$8.4 billion (10th–90th percentile range: US$6.3 billion–US$12.0 billion).

2.2 Scientific publications on CDR

In this section we use scientific publications and citations as early output indicators for R&D processes.

Scientific publications provide observable, standardized and comparable evidence of knowledge production.[7] Analysing the scientific publication landscape on CDR gives a bird's eye view of how research activities evolve over time and are distributed across the globe, as well as the extent to which they support development of individual CDR methods. Publications are also public goods that are accessible to other researchers. Citation counts reveal how knowledge flows through research systems, reflecting the broader impact of R&D investments and capturing knowledge spillovers.

Rapid growth in CDR publications

A large body of English-language scientific literature on CO_2 removal exists. Our database currently contains around 119,000 publications published between 2005 and 2025, the period covered in this report. The literature continues to be dominated by biochar, forest-based methods (i.e. afforestation, reforestation and forest management) and soil carbon sequestration, which together account for 77% of all unique CDR mentions in our dataset. Note that the volume of literature is substantially larger than reported in previous editions of this report due to improvements in the search strategy (see Box 2.1).

More than one-third (37%) of the publications in our dataset were published between 2023 and 2025 (2022 was the last year reported in *The State of CDR 2nd Edition*) (see Table 2.1). This share varies substantially across CDR methods. Some methods exhibit comparatively smaller shares – for example, forest-based methods (28%), BECCS (32%), and ocean fertilisation (22%). Other methods display larger shares – for example DACCS (56%), ocean alkalinity enhancement (60%) and direct ocean capture (68%) – indicating that much of the literature is very recent. Across the 44,000 new scientific publications on CDR released between 2023 and 2025, most deal with biochar (19,000), forest-based methods (10,000) and soil carbon sequestration (10,000). (Note that a single publication can discuss multiple CDR methods.) Interestingly, there were more publications dealing with DACCS (2,300; 4.5%) in recent years than with BECCS (1,600; 3.0%), even though the overall body of literature on BECCS remains larger. This is in line with trends in inventive activity as analysed in Section 2.3, potentially signifying a shift in early R&D activities away from BECCS and towards DACCS.

Number of CDR publications and long- and short-term growth rates by method, 2005–2025

	Publications, 2005–2022	Publications since SoCDR 2nd Edition, 2023–2025	Growth in annual publications, 2005–2022 (%)	Growth in annual publications since SoCDR 2nd Edition, 2022–2025 (%)*
Afforestation, reforestation, forest management	26,000	10,000	8.5	11
BECCS	3,300	1,600	17	5.2
Bio-oil storage	7	6	2.2	0
Biochar soil amendment	25,000	19,000	39	12
Biomass burial	29	24	10	-9
Biomass sinking	11	46	9.8	10
CDR (general)	2,100	1,500	16	19
DACCS	1,800	2,300	24	21
DOCCS	45	97	16	22
Durable wood products	800	390	9.4	13
Enhanced weathering	1,800	1,100	13	17
Mineral products	740	740	21	33
Ocean alkalinity enhancement	410	610	14	36
Ocean fertilization or artificial upwelling	990	280	-2.4	-8
Peatland and coastal wetland restoration	7,400	4,500	15	11
Soil carbon sequestration	19,000	10,000	13	16
CDR publications – Total**	75,000	44,000	15	13

***Table 2.1* Notes:** *CDR publication counts and growth rates. Numbers are rounded to two significant digits. CDR methods with higher recent (2022–2025) than long-term (2005–2022) rates of growth in annual publications are highlighted.*
**Calculating the growth rate since The State of CDR 2nd Edition requires the inclusion of data for 2022.*
***Total indicates the number of unique publications. Counts for methods represent unique mentions in publications.*

While the number of CDR publications continues to expand, average annual growth has slowed slightly to 13% in 2022–2025 from 15% in 2005–2022. Growth patterns vary considerably across individual CDR methods. BECCS, biochar, and peatland and coastal wetland restoration are among the CDR methods that exhibit lower annual average growth rates in the recent period (2022–2025) compared with the previous period (2005–2022). Other CDR methods – such as afforestation, reforestation and forest management, soil carbon sequestration and ocean alkalinity enhancement – show higher recent growth rates, indicated in darker colors in Table 2.1.

Average annual growth in scientific publications between 2022 and 2025 was highest for ocean alkalinity enhancement (36%), followed by mineral products (33%) and DACCS (21%). Lower growth rates were observed for BECCS (5.2%), forest-based methods (11%) and biochar (12%). Ocean fertilization and biomass burial are the only methods for which the number of publications decreases (-8% and -9% respectively), but for biomass burial, publication numbers are small and there is thus a high uncertainty in the trend. While forest-based methods and biochar represent relatively mature CDR research fields with already high publication volumes, the BECCS literature remains much smaller in scale.

We further analyse the regional patterns of CDR research publications by the location of the first author's main affiliation. Overall, 69% of CDR research is concentrated in three regions: Eastern Asia, primarily in China (33%), Europe (22%) and North America (14%). This trend is driven by the dominant role of Chinese scholarship in biochar research. For other regions with fewer CDR publications – namely Africa, Southern Asia, the Middle East and Eastern Europe – we observe a larger share of research in recent years, indicating faster growth.

For most world regions, we observe substantial shifts in research focus across different CDR methods in recent years. Figure 2.3c shows the shares of CDR research for each of the ten world regions between 2005 and 2022 and between 2023 and 2025. For example, DACCS research led by North American authors increased from 4% between 2005 and 2022 to 14% between 2023 and 2025. At the same time, the share of forest-based CDR research declined (from 30% to 20%), and the share for soil carbon sequestration dropped (from 21% to 16%). While Europe shows a similar decline in the shares of forest-based CDR publications (from 28% to 22%) and soil carbon sequestration (from 19% to 17%), we see a more gradual increase in research shares for biochar (from 23% to 27%), DACCS (from 2% to 5%) and peatland and coastal wetland restoration (9% to 10%). Africa witnessed a similar trend away from forest-based (from 31% to 25%) and soil carbon sequestration research (from 24% to 21%) towards biochar (from 36% to 42%) and DACCS (from 0.1% to 1.1%). Research patterns in Eastern Asia were much more stable and continued to strongly focus on biochar research.

Overview of CDR publications per method, 2005–2025

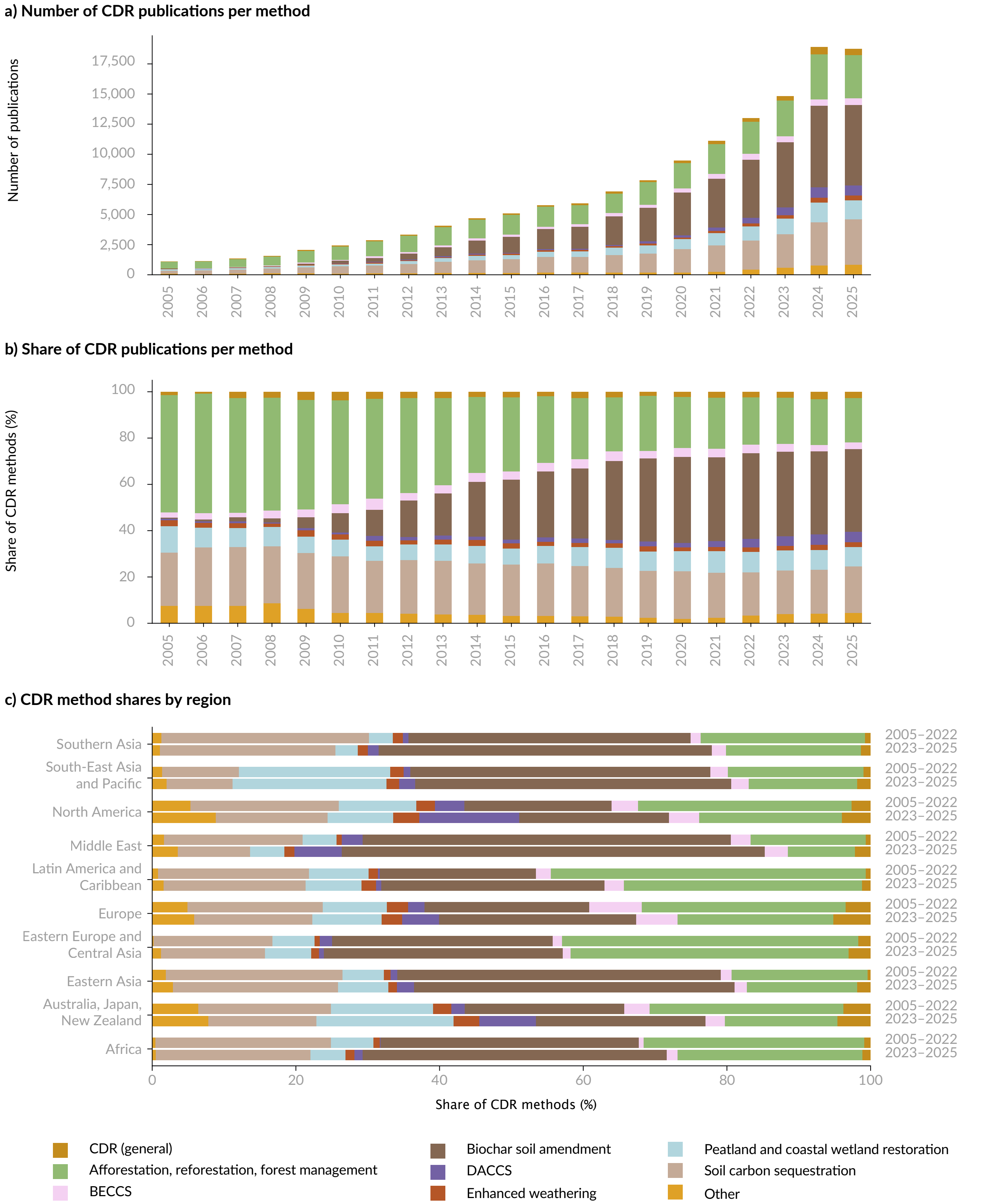


Figure 2.3 *CDR publications over time and by region: (a) total number of publications on CDR, (b) share of publications per CDR method over time and (c) share of publications per CDR method (2005–2022 and 2023–2025) per region of first author affiliation. The "other" category includes the following CDR methods: ocean fertilization, mineral products, alkalinity enhancement of water bodies, durable wood products, DOCCS, agroforestry, biomass sinking, biomass burial and bio-oil storage. Data for 2025 may be incomplete due to reporting lags.*

CDR cited more often than publications on low-carbon technology

As an addition to previous analyses, this edition of *The State of CDR* examines the wider impact of scientific publications about CDR by measuring how often they are cited in the scientific literature. The extent to which publications are cited is commonly used to quantify the intellectual influence or impact of scholarly works, authors and journals, and it can also be regarded as a measure of knowledge spillover. However, field-specific conventions and motivations beyond acknowledging intellectual influence caution against straightforward interpretations of results as a direct measure of influence.[8] As in other research fields, citations of publications on different CDR methods are very unevenly distributed. The least-cited 50% of publications only get 7% of all citations and the most-cited 10% get 54%. The number of citations also strongly depends on the year of publication, because it takes several years for publications to accrue citations.

To put the number of citations of scientific publications on CDR into the wider context of low-carbon technologies – broadly defined as technologies that reduce emissions, for example through renewable energy production, energy storage, energy efficiency and carbon sequestration – we use the citation frequency of low-carbon technology as our benchmark for the citation frequency of CDR publications (see the Technical Annex for details). However, a direct comparison can be driven by differences in the average age of publications, different journal outlets and other factors that influence citation numbers. Therefore, we use the methodology developed in Tripodi et al. (2024)[9] to correct for such confounding factors. The methodology controls for factors that have a strong influence on citations – matching each CDR publication to a low-carbon technology publication issued in the same publication year and in the same journal. It uses a negative-binomial regression approach and controls for other possible drivers of citations, including open access status and the number of authors.

CDR publications are cited 15% more frequently than comparable publications on low-carbon technologies. Significant differences emerge between low-carbon technology and CDR literatures at the level of individual CDR methods. The effect is largest for DACCS (+99%) and biochar (+36%) but also for general CDR literature (+73%). CDR methods less often cited than low-carbon technology include afforestation (-28%), peatland and coastal wetland restoration (-23%) and ocean fertilization (-33%). The citation patterns support a picture of CDR as a very dynamic and diverse research field, highlighting that CDR as a general topic – and especially novel CDR methods such as BECCS, DACCS, biochar and enhanced weathering – is gaining momentum as shown by the growing number of CDR publications and the greater extent to which CDR literature is being cited. Several factors may be responsible for the overall higher citation frequency, including that the total number of CDR publications is lower than the number focused on low-carbon technologies. This could increase the odds that any individual publication would be cited in an area of growing publication activity such as CDR.

Citation frequency of selected CDR methods compared to low-carbon technologies

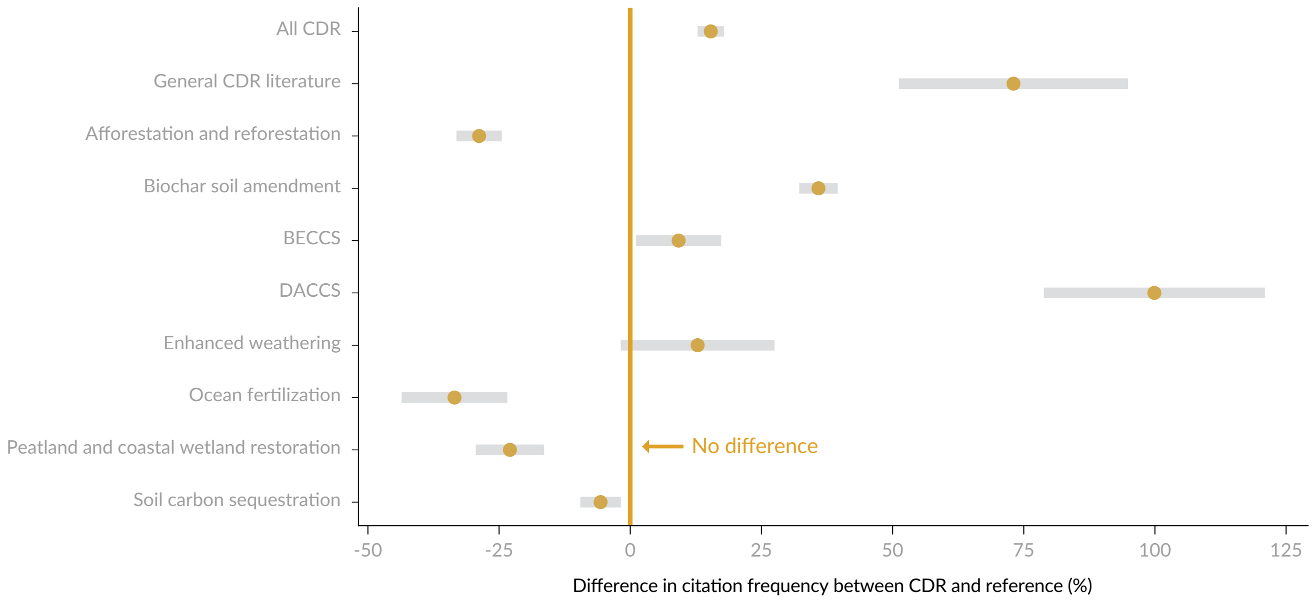


Figure 2.4 *Estimate of the difference in citation frequency of different CDR methods compared to low-carbon technologies. Central estimates are indicated as yellow dots and grey bars grey bars indicate 95% confidence intervals.*

Box 2.1 Methodological changes and effects on reported numbers of publications

The publication numbers reported in *The State of CDR 3rd Edition* are substantially higher than in previous editions for five main reasons.

1. This edition draws on four major bibliographic databases (Web of Science, Scopus, Dimensions and OpenAlex) rather than just one (large effect).
2. The search strategy for identifying CDR-relevant literature has been comprehensively revised and harmonized (large effect).
3. The literature has expanded significantly since the 2nd Edition (large effect).
4. The underlying databases have continued to expand their coverage of scientific sources (medium effect).
5. Several new CDR methods, including CCU pathways with long-term storage and ocean capture, have been added to the sample (small effect).

Compared to the 2nd Edition, these changes led to a substantial increase in the total number of publications identified for the period 2005–2022 (2nd Edition: 26,000; 3rd Edition: 75,000). The revised methodology particularly affected the total for forest-based CDR methods, which now show a similar total number of publications (36,000) to biochar (44,000) across the period 2005–2025. Despite the large increase in the total number of publications, both the yearly shares of CDR methods displayed in Figure 2.3a and the trends over time are broadly consistent with earlier editions. For more details on the methodology for this section, please refer to Technical Annex A.2.2.

2.3 Inventive activity (patenting)

Patents are a measure of inventive output and are often used as a proxy for innovation in the literature on technological change and the economics of innovation.[10–12] However, patents do not cover all inventive activity since not all inventions are patented or can be patented.[10,13] Patents are typically filed at the end of the invention process to protect the invention from being used commercially by others for a fixed period of time. Technical characteristics of inventions are described in detail in patent documents, enabling the analysis of technology developments over time. Patent families comprise multiple patents that relate to a single inventive output across regions or updates.[14] We analyse patent families – patents granted in at least two jurisdictions – as an indicator of high-quality inventive activity that we refer to as "patenting".[15] Patent classification is accomplished through machine-learning methods; details on how the approach has been refined since the 2nd Edition, including methodology and limitations, can be found in the Technical Annex.

Patenting for CDR inventions has decreased between 2011, the year in which CDR patenting reached a peak, and 2019, the last year for which we have patenting data that is not truncated. Initially, annual patenting increased by 11.3% per year between 2005 and 2011. Between 2011 and 2019, by contrast, we find an annual average rate of decline of 4.0% (see Figure 2.5a). Consistent with findings in the 2nd Edition, the decrease in CDR patenting is partly explained by the decline in BECCS patenting. In comparison, climate change mitigation patenting (as defined in the Technical Annex) increased gradually between 2011 and 2019 at a 2.2% annual average growth rate. In total, cumulative CDR patenting between 2005 and 2022 represents 0.8% of all climate change mitigation patenting during the same period.

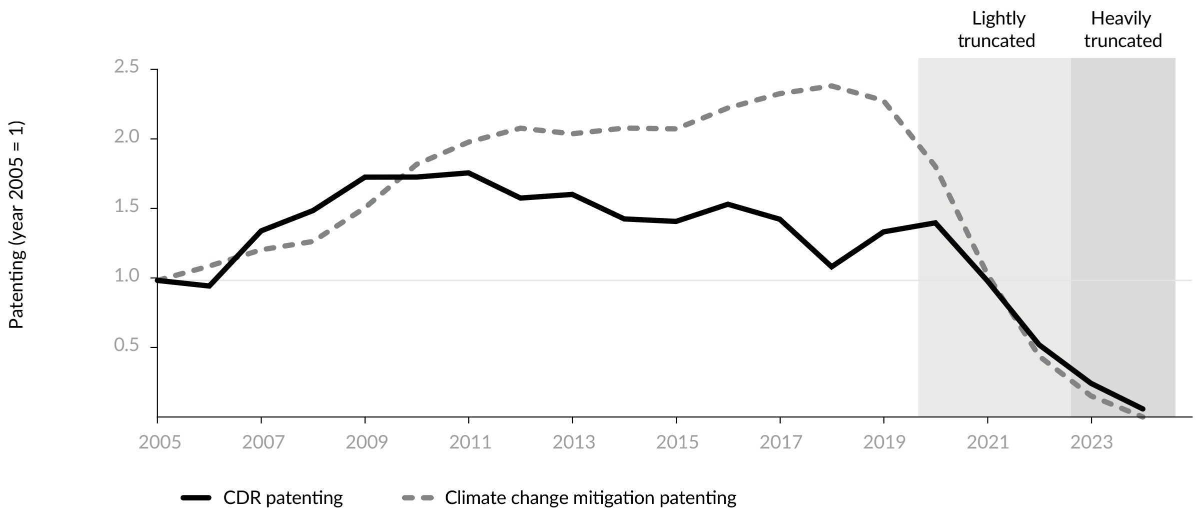
It is important to mention that the data from 2020 onwards is truncated. Granting a patent application may take up to five years after initial submission, and it takes time for a patent family to have its patents granted in multiple jurisdictions. We differentiate between lightly truncated (2020–2022) and heavily truncated (2023–2024) time periods. In the lightly truncated period, there is substantial patenting activity, but we still expect increases in the patenting numbers as additional patents are granted. However, we do not expect there to be a difference in the delay of granting patents depending on the CDR method and therefore we do not expect the distribution of patenting across the different CDR methods to change substantially during the lightly truncated period. In the heavily truncated period, both the quantity and distribution are likely to change, which is why we do not comment on either the total patenting numbers or share by technology during the heavily truncated period.

The decline in the share of BECCS patenting, which peaked at 42% of patenting in 2009, is shown in Figure 2.5b. We also find that the share of DACCS patenting has varied over the years, accounting for between 12% and 23% of all annual CDR patenting. Mineral products, which have been newly included as a CDR technology in the 3rd Edition, contribute a significant share of total CDR patenting, representing 14%–30% of annual patenting. The increase in biochar soil amendment patenting observed in the 2nd Edition continues, with its share of CDR patenting reaching 12% in 2020. Overall, the inclusion of additional CDR methods in the 3rd Edition analysis has the effect of reducing the relative share of those methods included in earlier editions.

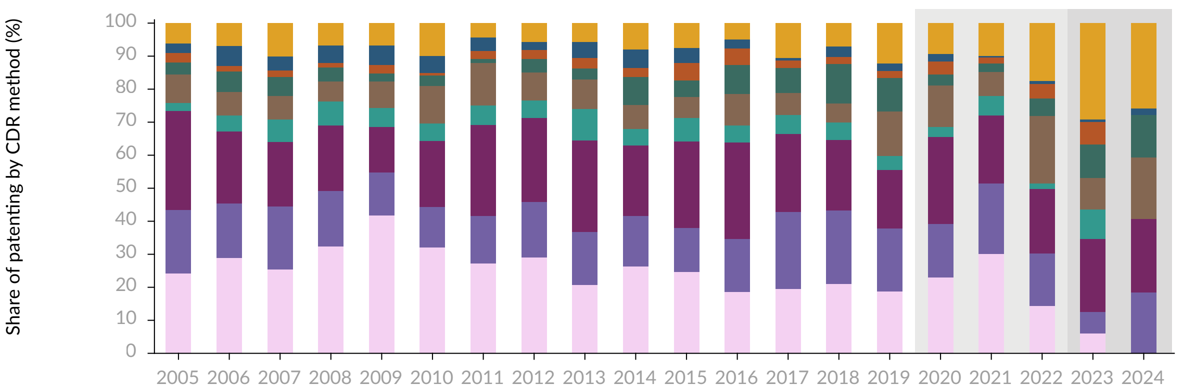
Turning to the geographic distribution of CDR patenting, we find that North America, Europe, Eastern Asia and Australia, and Japan and New Zealand are the four main regions where the inventors of a granted patent reside (see the Technical Annex), making up 93% of the total (see Figure 2.5c). There is considerable concentration in North America, which accounts for 38% of CDR patenting between 2005 and 2022, followed by Europe (31%). Eastern Asia accounts for 14% of all CDR patenting during the same period, while Australia, Japan and New Zealand combined account for 10%. The technological focus varies depending on the region. BECCS, for example, makes up a greater share of CDR patenting in North America and Europe, and mineral products are especially prevalent in North America and in Australia, Japan and New Zealand. In general, the share of CDR patenting by method in each of the regions investigated remains fairly stable over time.

Trends in CDR patenting, 2005–2024

a) Annual patenting trends in CDR and climate change mitigation technologies, 2005–2024



b) CDR patenting by method, 2005–2024



c) Geographic distribution of inventor locations in CDR patenting, 2005–2022

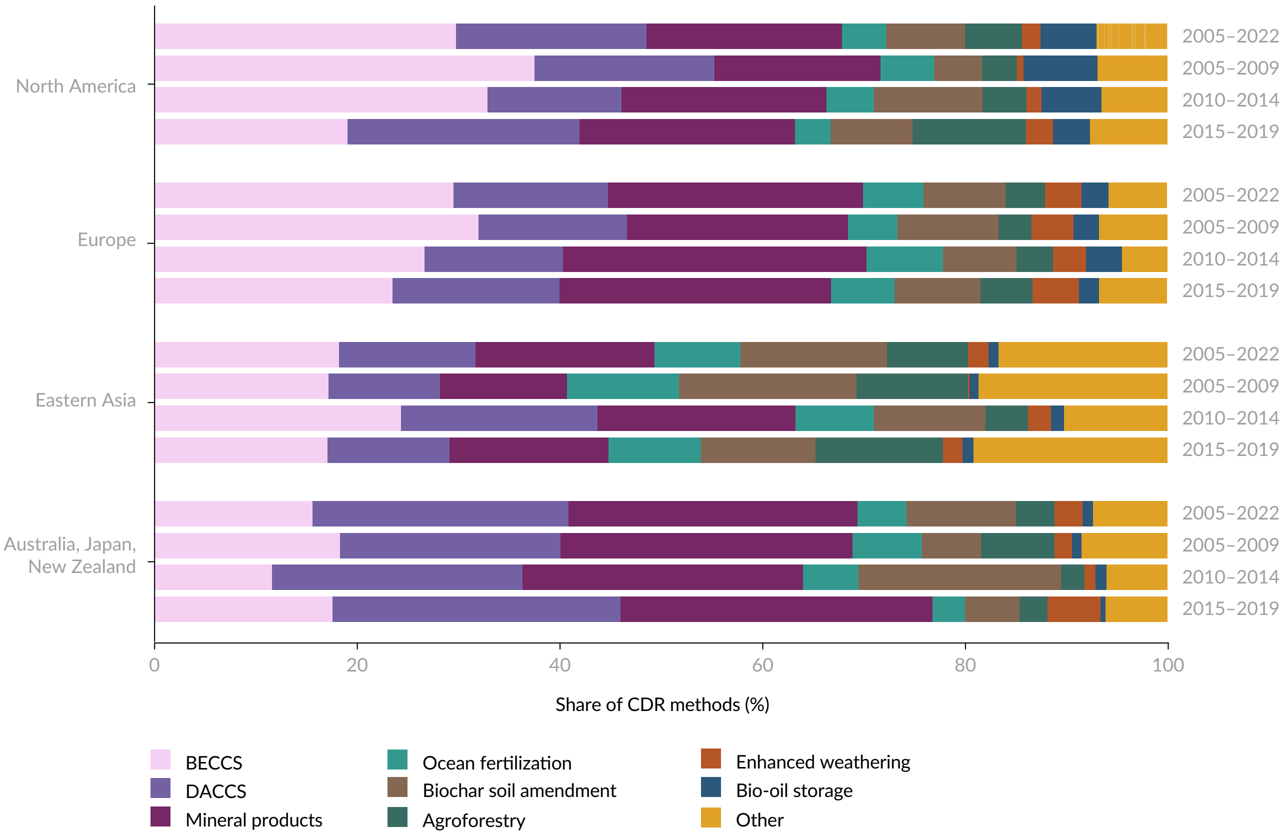


***Figure 2.5** (a) Patenting for CDR and climate change mitigation technologies between 2005 and 2024, (b) CDR patenting by method between 2005 and 2024, and (c) patenting by CDR method and region according to inventor location between 2005 and 2022. For CDR, only those patents that have at least one mention of a CDR method are included. Location refers to where inventors work and live, which may differ from their country of birth.*

Box 2.2 Methodological changes and effects on reported numbers of patents

In this edition of *The State of CDR*, we draw on patent data from the new, openly available EPO Technology Intelligence Platform rather than the PATSTAT dataset used in the last edition. Previously, patents were classified by CDR method using a single query to an online version of the GPT-4 model. The 3rd Edition uses an offline version of the llama3 model and classifies each CDR method several times to improve reliability (see the Technical Annex for details). We updated the CDR classes to align with the new list of CDR methods used in Edition 3 (see the Glossary).

Box 2.3 Limitations and knowledge gaps

- The estimates of investment in CDR research projects (see Section 2.1) do not reflect all research funding on CDR, as the Dimensions database only includes third-party projects and does not cover institutional funding from universities and other research institutes.
- The geographic coverage of the Dimensions database for tracking research grants is not fully transparent, and uncertainties remain over the scope of investments covered in some regions, such as Latin America, Africa and Asia. Similar uncertainties apply to the patent data from the EPO Technology Intelligence Platform.
- The approach used to search databases of grants (see Section 2.1) and scientific research publications (see Section 2.2) includes only research grants and articles with English-language titles and abstracts.
- The classification of research grants and publications by CDR method is not performed with very high accuracy, particularly for less frequently studied CDR methods, as there are fewer annotations with which to train the machine-learning classifier. Moreover, the machine-learning approach does not work equally well across all CDR methods and across time, which could lead to some biases in the numbers, particularly for CDR methods for which there is currently little research.
- Patents are only one measure of inventive activity, and many inventors may choose not to file for patents for their inventions.[10,13] This tendency may differ across countries and by type of CDR and low-carbon technology.
- While inventive activity as proxied by international patent families has been in slow decline since 2011, the raw number of individual patents has increased steadily. Due to concerns around patent quality, this report only shows international patent families. However, some CDR methods may be more likely to be patented than others depending on the actors, technology or region involved.
- Patent data is truncated to a greater extent than R&D grants and publications due to the duration of the granting process. Consequently, the data is likely to provide a less accurate reflection of the level of inventive activity from 2020 onwards and of its level and distribution across CDR methods from 2022 onwards.

2.4 Outlook

The previous sections separately presented the development of the three indicators covered in this chapter – grants, publications and patenting. Figure 2.6 synthesises these findings and compares their evolution over time (see panel a), their method-specific growth dynamics (see panel b) and their distribution by method in different geographical areas (see panel c). This comparison highlights the lack of a consistent signal across the CDR sector for a significant acceleration in R&D activities in recent years. Instead, the picture is diverse. Research input (funding) and output (publications) are more strongly aligned than either is with inventions. CDR-related grants rise and then stabilize and publications exhibit strong growth, while patenting activity has been declining over the last decade (see Figure 2.6a).

Similarly, the average annual growth rates for CDR method-specific subsets of research grants and publications are strongly correlated, while the growth rates in patenting were negative or only weakly positive for most methods (see Figure 2.6b). Finally, a majority of active grants and publications are focused on forestry, soil carbon sequestration, biochar and peatland and coastal wetland restoration. However, except for biochar, these CDR methods make up only a small percentage of CDR patenting during the same period (see Figure 2.6c). Instead, inventive activities focus mostly on CDR methods which may be subject to further technological improvements, such as BECCS, DACCS and mineral products, but also biochar.

The gap between the rising number of publications and grants and the gradual decline in patenting could reflect insufficient or uncertain incentives for commercialization and deployment as well as possible differences in patenting practices across CDR methods. Our data does not point towards the underlying reasons, but understanding these drivers will be important to accelerate early innovation in CDR. Examining the weight of different CDR methods in the three indicators across different geographies highlights how grants and publications show distinct but similar patterns in North America and Europe, while inventive activities are more aligned globally and focused largely on novel CDR methods. The strong research interest in biochar in Eastern Asia – mainly China – is also reflected in that method's larger share of biochar patenting and publications in the region.

The share of funding, publications and patenting covering different CDR methods has fluctuated over time, but some CDR methods are more prevalent than others. For example, most scientific publications have focused on biochar, forest-based methods and soil carbon sequestration, but the more recent growth has been in publications on enhanced weathering and ocean alkalinity enhancement. Regarding patenting, we see that a few CDR methods make up a majority of inventive activity over time with some fluctuations: BECCS represents the largest share but has been in relative decline since 2009, while the shares of patenting for DACCS, mineral products and biochar have reached double digits.

Synthesis of CDR trends and shares across indicators

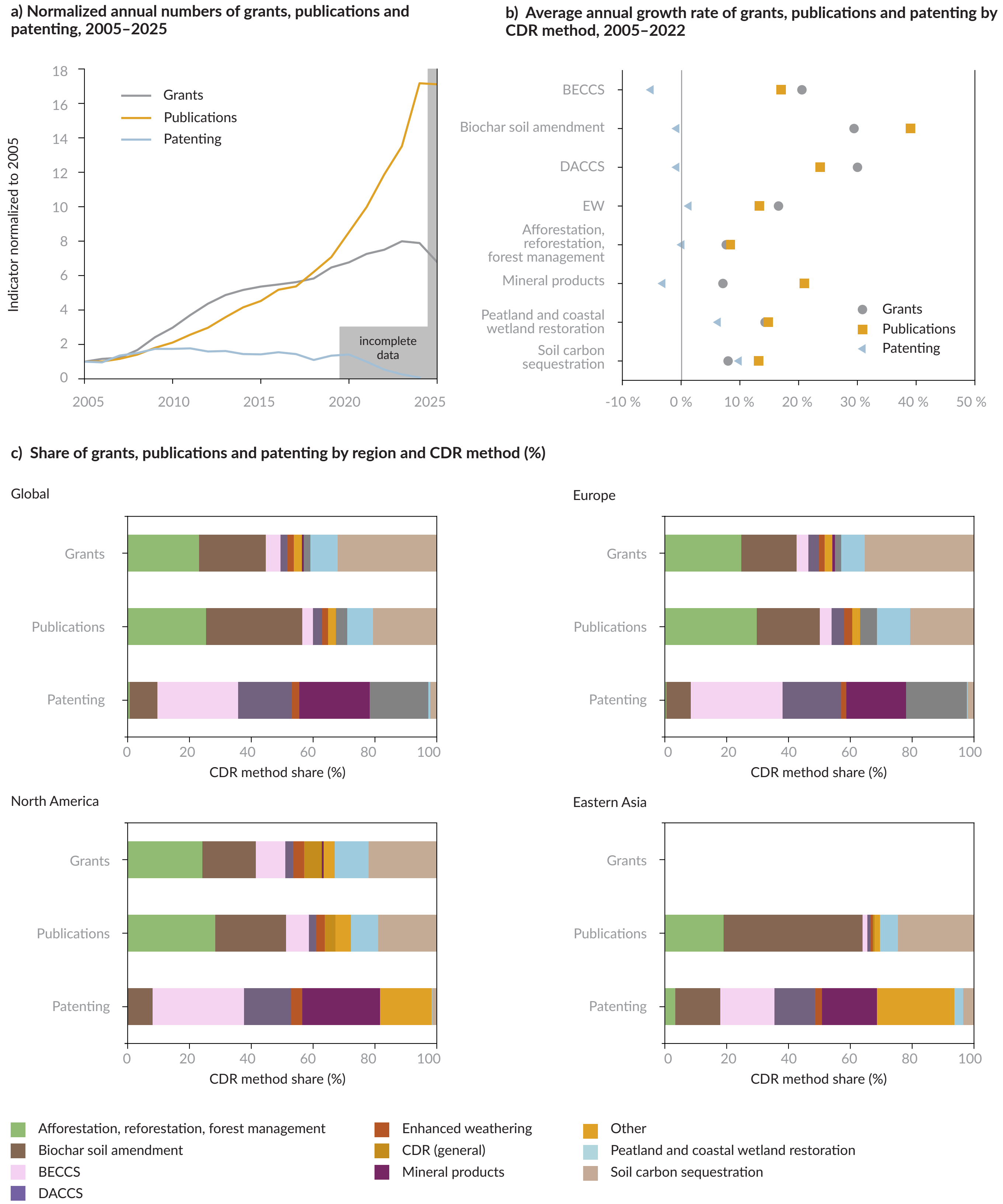


Figure 2.6 *Synthesis of trends and shares across indicators where comparable data is available: (a) normalized annual counts, (b) average annual growth rates across CDR methods, and (c) share by region and CDR method "Other" includes ocean fertilization, alkalinity enhancement of water bodies, durable wood products, DOCCS, agroforestry, biomass sinking, biomass burial and bio-oil storage.*

There may be benefits in fostering the development of a broad portfolio of CDR methods through a combination of supportive R&D policies and increased incentives for deployment, which would also incentivize R&D activities. Such a portfolio approach could help align research activities and outcomes with different regional capabilities and needs. Steering research efforts through policy development processes could help build a robust knowledge base, overcome early-stage barriers, identify negative impacts and prepare promising technologies for large-scale deployment. Here, the design of R&D funding and early deployment policies to support CDR can build on experience with other low-carbon technologies.[16,17]

Overall, the status of CDR in early-stage innovation is uneven. We do not find consistent signals of a significant acceleration in R&D activities. While research grants and scientific publications continue to grow, with the latter expanding at a much higher rate, much CDR R&D funding still comes from co-funding grants rather than from grants dedicated to CDR. We also find that inventive activity as measured by patenting has declined slightly in the period up until the last year without truncated data (2020), in contrast to slight growth in climate change mitigation patenting.

While *The State of CDR 3rd Edition* finds no strong evidence of a step-change in early-stage innovation for CDR, it is still possible that such signals may emerge in future. Since 2020, CDR has taken on a much greater role in discussions on climate policy, a shift that may become measurable, particularly in the patenting record, by the time of the next edition.

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Chapter 3

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Buffer vessel from a modern biomass plant. By Kontrast-fotodesign

Chapter 3 | Demonstration and upscaling

Demonstration projects, new firms and investments, workforce development and expectations of growth are key to scaling up CDR. Steady development is evident in many areas – but so, too, are recent reversals in policy support and company targets.

Key insights

- The number and capacity of demonstration plants have grown dramatically in recent years, and support for projects is strengthening in many countries – but it has weakened in the United States due to uncertainty surrounding its DAC Hubs Program.
- Investment in CDR companies rebounded in 2025 – and its share of all climate-tech funding grew to 2.6%. This trend is driven by a surge in grants from public and quasi-public institutions and debt financing, highlighting the volatility of the CDR innovation ecosystem.
- CDR companies require a diversified, skilled workforce, with substantial variation in the number and type of job postings across methods. There is high demand for engineering and technical roles as well as for sales, operations and finance.
- CDR companies and industry groups have announced capacity targets that show the ambition to reach 5.29 Gt per year of novel CDR capacity by 2050. Still, some targets have been revised downwards, highlighting uncertainty about whether long-term company goals will be realized.
- Meeting long-term goals for novel CDR, including those implied by publicly stated company ambitions, will require fast scale-up rates. These rates are not unprecedented, but they are at the high end of historical examples of technology scale-up.
- A broad range of indicators suggest that, despite recent reversals, the CDR innovation ecosystem is advancing towards the market growth phase, as evidenced by new demonstration projects and large investments in startups, but stable policy support will be crucial to future upscaling.

CDR demonstration and upscaling sit at the intersection of innovation and widespread deployment. As technologies transition from the early-stage research and development phase (see Chapter 2) towards the market growth phase (see Chapter 7), this chapter captures the critical intermediate stage in which technical viability meets market reality. With this focus, we examine CDR activities by both established companies and startups as drivers of CDR upscaling. We track this progress through several key indicators including:

- Public funding of demonstration projects that provides essential early-stage support to de-risk novel technologies;
- Investment in CDR companies that reflects market confidence and capital mobilization to enable deployment; and
- Company announcements of capacity targets that reveal industry ambitions and expected growth pathways.

We also discuss emerging needs to support upscaling, including workforce development, business and sales models, and subnational policies and programmes.

3.1 Evolving public demonstration programmes

The demonstration of novel technologies is an important stage in technology innovation. Demonstration and pilot projects enable real-world experimentation outside the lab and learning opportunities in the settings where technologies may be widely adopted. Demonstration projects are typically larger in scale than pilot projects and are sometimes referred to as “first-of-a-kind” (FOAK) projects. Government funding provides stability and support for technologies that have not yet been widely adopted and may benefit from additional testing outside the lab before commercial-scale operations.

This section is focused on public funding for pilot and demonstration projects. Some programmes and technologies included in this section are not necessarily CDR but rather enabling technologies that may be directly relevant to the development of CDR, such as carbon storage and transport. The final destination for captured carbon is not always specified for demonstration projects, but these projects can still provide lessons for CDR. In this section, we refer to methods such as BECCS or DACCS broadly, even if the fate of the captured carbon is not specified. The first subsection summarizes projects that have either begun or announced the start of operations between 2020 and 2030. The second subsection describes public funding programmes in countries that either have dedicated public funding for demonstration projects or have provided such funding on another basis. Beyond national governments, subnational governments – including, critically, cities – also have a role in upscaling CDR, through funding support and other policies (see Box 3.2).

Trends in demonstration projects

Demonstration projects provide opportunities for stakeholders across the public and private sectors to test, understand and improve novel technologies before commercialization and after lab-scale testing.[1] Most novel CDR projects now in operation, with the exception of biochar, are in the demonstration phase. Because learning is a motivation for demonstration projects, global collaboration across countries is particularly important.

Mission Innovation is a global initiative that supports technology innovation through research, development and demonstration, with an objective of accelerating progress towards meeting the Paris Agreement goals. The programme aims to foster learning and cooperation among Mission Innovation member countries to support the development of clean energy technologies that contribute to net-zero goals. Mission Innovation was launched in 2015 with its membership comprising the European Union and 15 individual countries – a number that has now grown to 22. Among Mission Innovation's seven specific focal areas is the CDR Mission. The CDR Mission was launched in 2021 and is co-led by the United States, Saudi Arabia and Canada. An additional five countries are core CDR Mission members, and two countries and the European Commission are part of the CDR Mission support group.

One pillar of the CDR Mission is the CDR Launchpad, which is a coalition of governments that have committed to supporting CDR demonstration projects. Countries that are a part of the Launchpad have pledged to build at least one CDR project with a removal capacity of at least 1,000 tonnes of CO_2 per year by 2025, share data on these projects, and provide a combined total of US$100 million for pilot and demonstration projects globally. Canada, the European Commission, Iceland, Japan, Norway, the United Kingdom and the United States have all joined the CDR Launchpad. The Mission Innovation CDR Launchpad represents the only dataset specifically focused on tracking announced CDR demonstration projects, although data is limited to Launchpad members.

Because data on demonstration and pilot projects is patchy and not kept in a centralized repository, we have gathered information from multiple sources to create our own dataset. Specifically, we have collated data from the Mission Innovation CDR Launchpad[2] (last updated in October 2024), updates from the 16th Clean Energy Ministerial[3] and 10th Mission Innovation Ministerial meetings, the International Energy Agency (IEA) carbon capture, utilization and storage (CCUS) Projects Database and the *IEA State of Energy Innovation 2025* report.[4,5] Our dataset includes 46 announced projects that span many CDR technologies: BECCS, DACCS, enhanced weathering, biochar, mineral products and DOCCS (see Figure 3.1). Approximately 80% of these projects have an announced removal capacity in excess of 1,000 tonnes per year.

Demonstration projects announced, under construction or in operation, 2020–2030

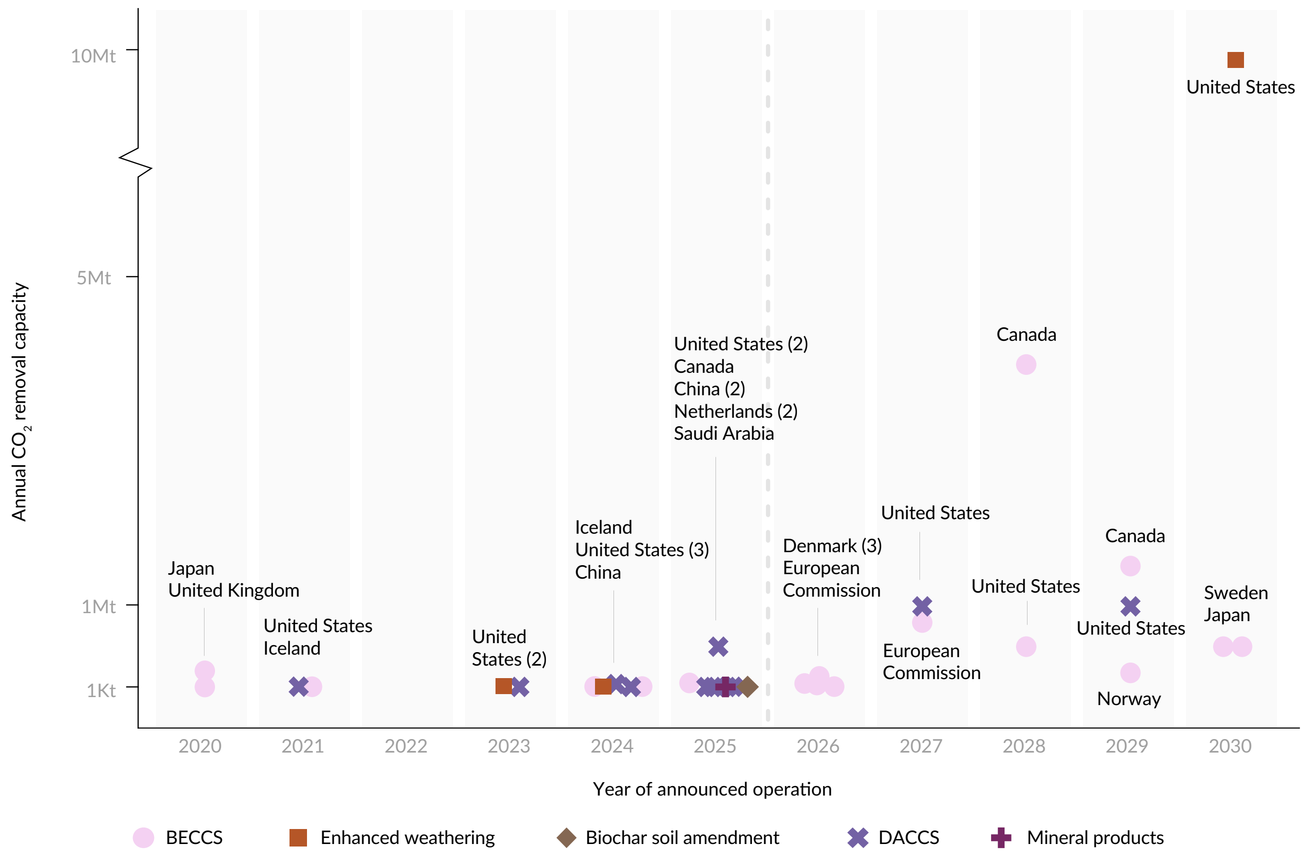


Figure 3.1 *Removal capacity and year of announced operation for demonstration projects. This figure includes only demonstration projects that have reported both a removal capacity and a year; other projects have been announced but lack one or both of these data points. Demonstration projects with an announced year of operation before 2026 are only shown if they are operational or under construction. The Mikawa Plant in Japan is shown, although the captured CO_2 is not yet being durably stored, and the Nian'da biochar project in China is shown, although it is a prototype. The number of projects per country is one unless otherwise noted in parentheses.*

The removal capacity of announced demonstration projects has increased over time (see Figure 3.1). Projects use a variety of novel CDR methods, but BECCS is the most common type of project after 2025. Five DACCS projects and five BECCS projects with a removal capacity of at least 1,000 tonnes are in operation or under construction. The largest announced demonstration project is the Eion enhanced weathering project in the United States, with a planned removal capacity of 10Mt by 2030.

The State of CDR 2nd Edition used Mission Innovation data from February 2024, which at that time was the latest available. Since then, nine new projects and seven updates have been added to the Mission Innovation CDR Launchpad. Although the Launchpad data was last updated in October 2024, it remains the most current available source. Projects were updated either through a change in their projected annual removal capacity or their year of first operation. One DACCS venture, Project Bison, was planned to be built in Wyoming, United States, but was paused and therefore not included in the most recent Mission Innovation data. In a press release, the chief executive officer of CarbonCapture, the company developing the project, stated that competition for clean power from data centres and the cryptocurrency industry in Wyoming was the reason for the pause.[6] CarbonCapture has also moved a DACCS pilot plant, originally announced in the United States, to the Deep Sky Alpha centre in Canada.

Iceland and the United States have built operational novel CDR projects with removal capacity greater than 1,000 tonnes. The Deep Sky Labs DACCS project in Canada is under construction but is not yet operational. The carbon capture component of the BECCS Mikawa Plant in Japan is operational, but the removed CO_2 is currently not being stored underground. China, which is part of the CDR Mission but is not a member of the CDR Launchpad, has built a biochar pilot prototype with a removal capacity of 1,500 tonnes per year. Six other demonstration projects are currently operational, but each is below the 1,000-tonne removal capacity threshold. These projects all provide lessons for other countries and projects moving forward, a particularly important goal for demonstration projects. Thirteen additional projects were announced with an initial goal to begin operation by 2025 but have not yet been built. While some of those projects have begun front-end engineering studies, are undergoing lab testing or have announced a delay, most were announced without much additional information and their status is unclear. In all, we estimate that 59% of the demonstration projects that announced removal would begin in 2025 were either in operation or under construction by early 2026.

Government funding of CDR demonstrations

Because novel technologies carry no guarantee of success – especially before they are ready to be widely deployed – government support can be important to reduce investment risks. National and regional governments have developed various strategies to support CDR demonstration projects. Some have focused on programmes that specifically support CDR, while others fund CDR demonstration projects through broader clean energy, carbon management or carbon capture programmes.

The IEA estimates that US$5 billion in R&D funds for CDR projects has been announced globally.[6] This includes programmes that began between 2019 and early 2025, with funding to be dispersed through 2040. Our tracking of public research, development & demonstration (RD&D) is updated through early 2026 and totals US$5.4 billion, which includes funding awarded to two DAC hubs in the United States (see Box 3.1). If the US DAC Hubs Program is fully funded, total announced RD&D funding between 2019 and early 2026 would reach US$7.9 billion. Some of this funding has been awarded to projects that capture carbon from ambient air but do not necessarily include plans to durably store carbon.

Since *The State of CDR 2nd Edition*, total government funding for CDR demonstration projects has grown substantially. The number of countries that have provided financial support for demonstration programmes has also grown. We present profiles of funding for CDR demonstration projects for 12 countries and the European Union, an increase of six countries since the last edition. To our knowledge, this is a complete list of countries and regions with public funding for CDR demonstration projects as of February 2026. Each has funded CDR demonstration projects through either a state-owned enterprise or a public programme. The discussion in this chapter focuses specifically on funding for demonstration projects; research and development efforts and other CDR policy mechanisms are further described in Chapter 2 and Chapter 5.

The types of funding efforts supporting CDR are diverse. Programmes with small carveouts for CDR projects, such as Emissions Reduction Alberta in Canada and the CLIMIT programme in Denmark, allocate climate funding to specific CDR projects. In contrast, programmes like the Innovation Fund in the European Union and the DAC Hubs Program in the United States provide much larger sums to support demonstration projects. Two programmes together provide 70% of global funding for CDR demonstration and pilot projects: the US DAC Hubs Program at 44% (if all originally allocated funding is awarded) and the reverse auction programme in Sweden, which focuses on operational subsides for BECCS projects, at 25%. Given the large contributions of these two programmes, DACCS and BECCS are receiving a majority of public funding support for demonstration projects. Despite a global trend of increased governmental support for CDR demonstration projects, support at the national level is highly variable. For example, in Sweden, US$3.8 billion will be awarded to BECCS projects between 2026 and 2046. On the other hand in the United States, support for CDR – including the future of the US DAC Hubs Program – is uncertain and greatly clouds the overall picture of global RD&D funding for CDR projects (see Box 3.1).

Australia

Australia has several funding streams, mostly focused on carbon capture and sequestration – although many CDR projects also have received public support.

In 2022, the Australian Government invested A$30 million (US$19 million) to establish the CarbonLock Program, Australia's leading novel CDR research program. Prior to this, in 2021, the Carbon Capture, Use and Storage Development Fund supported six projects totalling A$50 million (US$32 million). This included A$9 million[7] (US$5.8 million) for Energy Developments Pty Ltd., a BECCS project, and A$4 million[7] (US$2.6 million) for the AspiraDAC pilot project. In 2024, through the Carbon Capture Technologies Program,[8] the Australian Government invested A$65 million (US$42 million) in seven demonstration projects. About A$30 million (US$19 million) of this funding was for four DACCS projects.[9] A second round of funding through this program is anticipated to open in 2026.

At the state government level, the Government of Western Australia is funding CDR projects through the A$34 million (US$22 million) Lower Carbon Grants Program. The effort has funded[10] the CSIRO Carbon Capture Material Acceleration Centre with A$5 million (US$3 million) and the Biomass Projects Pty Ltd. biochar project with A$9 million (US$6 million). The Government of Western Australia is also funding pilot projects focused on carbon sequestration under the A$15 million (US$10.5 million) Carbon Innovation Grants Program[11] and mineral carbonation projects through the A$2.5 million (US$1.6 million) Accelerated Mineral Carbonation Research Program.[12]

Canada

Canada has several funding streams to support RD&D for CCU, CCS and CDR. Natural Resources Canada (NRCan) received Can$319 million (US$226 million) in funding from 2021 to 2028 to support CCU/S RD&D, including CDR.[13] These monies have supported DACCS, BECCS and enhanced mineralization projects, although most have focused on research and development with some funding allocated for pilot and demonstration projects.[14] For example, NRCan provided Can$5.3 million (US$3.8 million) to support a front-end engineering design study for a demonstration plant at the former Hinton Pulp Mill in Alberta,[15] which also received Can$3 million (US$2 million) in additional funding from Emissions Reduction Alberta to support BECCS demonstration. In 2024, NRCan provided Carbon Engineering with Can$5 million (US$3.6 million) in funding to demonstrate all-electric DACCS systems.[16] In 2026, NRCan launched a new call for proposals for a CCU/S front-end engineering and design (FEED) study, for which CDR projects are eligible;[17] the goal is to support projects in advancing from late-stage demonstration to final investment stages.

In addition, Emissions Reduction Alberta provided Can$5 million (US$3.6 million) to Deep Sky Alpha, the world's first direct air capture innovation and commercialization centre.[18] Deep Sky provides CDR companies with infrastructure such as land, energy and storage capacity, as well as support for permitting and removal credit sales.

China

CDR activities in China are concentrated at the research and pilot scale, with growing coordination across ministries, state-owned enterprises and academic institutions. The Ministry of Science and Technology is a member of Mission Innovation and submitted an update in August 2025 on its CDR policies, programmes and projects. State-owned enterprises are participating in several projects. For example, China National Petroleum Corporation is constructing a 1,000-tonne-per-year DACCS pilot plant and China Energy Engineering Co. Ltd. is operating a 600-tonne-per-year DACCS pilot in collaboration with Shanghai Jiao Tong University.[3]

Denmark

Denmark is supporting CDR projects through two mechanisms – the Carbon Capture Utilization and Storage Fund and the Negative Emissions Carbon Capture and Storage Fund. Both funds have previously supported CDR projects. The CCUS Fund provided DKr 8 billion[19] (US$1.2 billion) in funding to the Ørsted Kalundborg CO_2 Hub, which is a BECCS project. The NECCS Fund has supported an additional three BECCS demonstration plants[20] with a total of DKr 167 million (US$25 million) from the Danish government. The amount of funding actually disbursed through these mechanisms depends on the tonnage of carbon removed.

European Union

Several EU member countries have their own policies and programmes that support CDR demonstration projects. The European Union also provides funding through the European Commission, its executive arm, including via the Innovation Fund. In 2025, Danube Removals[21] received €50 million (US$58 million) from the Innovation Fund to support a large-scale BECCS project. Two projects that include elements of the CDR value chain received funding in 2021: the Silverstone mineral storage project, which includes the storage of captured carbon from direct air capture (DAC) plants, received €4 million (US$5 million) and BECCS Stockholm received €180 million (US$207 million). The Coda Terminal, which encompasses the shipment of captured carbon to Iceland for storage using Carbfix's enhanced mineralization process,[22] received €115 million (US$132 million) in 2022.

Germany

The German parliament approved a 2026 federal budget that includes €98 million (US$113 million) to support CDR projects and an additional €11.5 million (US$13 million) to fund the purchase of carbon removal credits.[23] The government has earmarked another €320 million (US$368 million) to support CDR efforts from 2027 to 2033. It is unclear how much of this funding will be allocated to demonstration projects.

Japan

The New Energy and Industrial Technology Development Organization in Japan supports RD&D efforts in CDR, including demonstration projects, through the Moonshot Research and Development Program.[24] The total funding for the programme is ¥50 billion (US$320 million), of which a small amount has been allocated to CDR projects. This includes DACCS projects and enhanced weathering projects. Japan has also supported the Mikawa BECCS plant,[25] which has the capacity to capture about 180,000 tCO_2 per year.

Japan is also funding biochar, carbon sequestration in wood materials and coastal wetland restoration projects through its Ministry of Agriculture, Forestry and Fisheries. The Development of Negative Emissions Technologies in Agriculture, Forestry and Fisheries Industries programme[26] includes ¥16 billion (US$102 million) to support biochar projects.

Netherlands

The Netherlands has two major programmes to support CDR demonstration and pilot projects. The Demonstration Energy and Climate Innovation programme[27] provides subsidies for pilot and demonstration projects, including for CDR projects. It has a budget for project support of €100 million (US$120 million). The Stimulation of Sustainable Energy Climate Transition (SDE++) programme[28] includes subsidies for energy production and the reduction of CO_2 emissions; BECCS and DACCS plants are eligible to apply for these subsidies. The 2025 budget for SDE++ is €8 billion (US$9.6 billion).

Norway

Norway has several streams of RD&D support for CDR projects. The CLIMIT programme is a partnership between Gassnova and the Research Council of Norway that supports RD&D efforts for CCU/S technologies. The programme has historically been focused on CCU/S projects, although some BECCS and DACCS research has also been funded. In 2025, for the first time, NKr 10 million[29] (US$980,000) was specifically earmarked to support CDR RD&D, including support for industrial projects, though no allocations have been announced.

The first grant to support a DACCS project in Norway was granted in 2023 by Enova, a state body owned by the Norwegian Ministry of Climate and Environment. Enova allocated NKr 36 million[30] (US$3.5 million) to support the Removr DACCS demonstration plant.

Saudi Arabia

Saudi Arabia sponsored a DACCS demonstration unit inaugurated by Climeworks and the King Abdullah Petroleum Studies Research Center in Riyadh in 2025.[31] Separately, Saudi Aramco, a majority state-owned energy company, is funding a pilot DACCS plant in Dhahran that was developed with Siemens Energy and launched in 2025.[32]

Sweden

The Swedish Energy Agency has supported several CDR RD&D initiatives, including pilot and demonstration projects, funded in part through a BECCS reverse auction programme.[33] For example, Stockholm Exergi is due to receive SKr 20 billion (US$2 billion) over 15 years once it begins geological storage of carbon captured at its bioenergy-generation plant in Stockholm, a step planned for 2028.[34]

The Swedish Energy Agency's Industrial Leap initiative[35] includes a funding stream for BECCS demonstration and pilot projects totalling SKr 1.3 billion (US$143 million) for 2025 to 2031. Through this initiative, the agency is funding the Söderenergi BECCS project with SKr 75 million (US$8 million).[36]

United Kingdom

The Greenhouse Gas Removal Demonstrators programme[37] is a multi-departmental initiative in the United Kingdom with £32 million (US$42 million) budgeted from 2021 to 2026. This programme includes the development of CDR demonstration plants with a budget of £23 million (US$30 million). The UK Department for Energy Security and Net Zero administered the DAC and Greenhouse Gas Removal Innovation Programme from 2020 through 2025, totalling £54 million (US$70 million).[38] The programme consisted of two phases, with phase 1 supporting 24 feasibility studies and phase 2 funding 15 pilot and demonstration projects.[39]

The UK Department for Energy Security and Net Zero and the Department for Business, Energy and Industrial Strategy administered the Hydrogen BECCS Innovation Programme from 2022 to 2025. The programme proceeded in two phases, the first focused on scoping and development and the second on supporting demonstration projects. The second phase included £26.2 million (US$34 million) awarded to six projects.

United States

The United States allocated US$3.5 billion towards four large-scale DAC demonstration projects through the DAC Hubs Program.[40] DAC hubs are demonstration projects, either individual projects or several interconnected projects. In 2023, two DAC hubs were issued funding totalling US$1.2 billion to build demonstration plants. Funding for the other two DAC hubs has not been awarded, and their funding status was uncertain as of April 2026. Also uncertain was the status of the two DAC hubs that were awarded funding, as many previously awarded clean energy and climate projects were cancelled in 2025 (see Box 3.1).

The United States has several other public funding streams that support CDR demonstration projects in the country. Through the Carbon Negative Shot strategy, the Department of Energy has a budget of US$100 million for 2024 to 2029 that includes support for five small BECCS pilots and ten enhanced weathering pilots. The CDR Purchase Pilot Prize, which began in 2023, was allocated US$45 million in 2026 that could support demonstration projects by spurring demand for CDR credits. Additionally, the Department of Energy has allocated US$71.5 million to RD&D pathways for CDR technologies and approaches.[41]

Box 3.1 Changes in the funding landscape for CDR demonstration projects

Public funding for CDR demonstration projects has expanded into new regions, including China and Saudi Arabia, but it has contracted in others, and funding instability and uncertainty are emerging as key barriers. An example of expansion is the Swedish government, which is supporting BECCS demonstration and deployment through a robust programme with SKr 36 billion (US$3.6 billion) of funding expected between 2026 and 2046.[42] The EU's institutional framework, in contrast, remained comparatively stable but financially exposed. While the Innovation Fund,[43] Europe's largest mechanism for industrial decarbonization and carbon management demonstration, maintains a robust policy framework that offers broad eligibility for CDR and CDR-enabling services, it lacks a dedicated funding stream for CDR demonstration projects. Furthermore, because the Fund's revenues derive from EU ETS allowance auctions,[44] funding levels remain sensitive to carbon price[45] and auction volume fluctuations, affecting the scale and predictability of grants.

In the United States, the federal funding landscape for CDR has grown increasingly vulnerable. The Inflation Reduction Act in 2022 and the Bipartisan Infrastructure Law in 2021 both specifically supported CDR demonstration projects. The future of the DAC Hubs Program, once the largest funding effort in the world dedicated specifically to CDR demonstration projects, has become uncertain.[46] The Department of Energy terminated more than US$3 billion in previously awarded clean energy and carbon management projects,[47] including several related to CCU/S. In response, some of the intended recipients have filed lawsuits.[48] These developments have further intensified uncertainty in the United States about public funding for climate initiatives, including CDR demonstration projects.

Overall, funding for CDR demonstration projects currently depends less on technological readiness than on institutional continuity. Policy reversals, market-dependent revenue streams and fragile international finance mechanisms have each introduced instability that could limit the capacity of CDR operators to move beyond the pilot stage and upscale over time.

Box 3.2 Upscaling CDR subnationally and in cities

Subnational actors, particularly cities, are playing an increasingly important role in funding, permitting, planning and goalsetting around CDR, as well as in establishing polycentric and multi-level governance networks. For these actors to achieve net-zero goals,[49] CDR is essential, potentially turning them into catalysts of CDR upscaling. Prominent examples of subnational action that may spur urban CDR include a push for 100 European cities to achieve climate neutrality by 2030 with support from the EU's Horizon Europe innovation funding programme mission focused on climate-neutral and smart cities;[50] the separate emissions reductions and carbon removal goals set by the State of California;[51] and the 4 Corners Carbon Coalition,[52] a collaborative effort among local governments in the Western United States to fund CDR projects. Cities can be sites of experimentation and learning, both for peer cities and countries, to understand the benefits and drawbacks of different approaches to CDR scale-up.

In cities, CDR can be integrated directly into the systems that shape urban life, such as planning, infrastructure and governance – rather than treated as a stand-alone intervention that may be missing from the priority lists of urban policymakers and lacking in dedicated funding sources. In this view, CDR becomes a channel for urban-scale synergy actions and co-benefits, aligning climate action strategies with other urban targets such as street-level cooling, air pollution or stormwater management.[53–55] Early estimates suggest that a portfolio of CDR of up to 1 $GtCO_2$ per year[56] is possible – including carbon storage potentials from vegetation, soils and the built environment, as well as the capture potential for decentralized DACCS – and also suggest synergies with other policy objectives as potential alternative entry points.

Cities are operationalizing CDR through a combination of approaches:

- Land-based approaches (e.g. urban afforestation[57–59] in Freetown,[60] Melbourne[61] and Navi Mumbai[62]) and peatland and coastal wetland restoration in Yokahama;[63]
- Integration of carbon-storing materials into the built environment[64,65] (e.g. biochar in soils, asphalt and concrete, as in Basel[66] and Helsingborg[67]); and
- Ownership or coordination of facilities for biochar (e.g. in Minneapolis[68]) and BECCS (e.g. in Oslo,[69] Lahti[70] and Stockholm[71]).

Crucially, many of these efforts rely on partnerships and co-finance with other municipal or regional governments, research institutions, expert organizations and higher-level public agencies to provide governance capacity, research and innovation support, robust MRV and access to finance, enabling cities to translate CDR potential into durable and scalable implementation.

3.2 Growth in the CDR start-up ecosystem

Startups are important actors within the innovation ecosystem because they can quickly bring new products and services to market. However, they face many well-known challenges when trying to move a new technology from the demonstration stage to initial commercialization and market growth.[72] Various financing mechanisms in the public and private sectors can address these challenges.[73] Startup funding occurs in consecutive rounds, typically increasing in dollar amount. The first grant or seed funding is used to fund precommercial, high-risk technologies. Grants are most often provided by public entities, and seed funding commonly comes from specialized investors such as venture capital or "angel" investors. Next are series A and B equity rounds, which typically occur when commercial development has started but deployment is limited. After early-stage financing, startups may seek growth equity funding, which tends to provide the higher dollar amounts needed to expand operations.[74] Because growth equity funding comes once technologies are more developed and risks are lower, these rounds have higher rates of participation by corporations and non-specialized financial sector actors. To support large-scale diffusion, companies then take on debt[75,76] and, finally, may exit through mergers, acquisitions or buyouts to transfer ownership to another company – or through initial public offerings to become publicly owned.

CDR startups and investment

This section examines the formation of CDR startups and investments in CDR companies through the end of 2025, as reported in the Net Zero Insights (NZI) database.[77] NZI integrates automated data collection, direct company submissions and manual validation to track investment flows across climate technologies (i.e. climate-tech). NZI categorizes companies in a taxonomy of climate-tech solutions, including GHG removal. We collect data on companies within this GHG removal category as well as the carbon offsetting and carbon market categories. We use a combination of automated and manual categorization techniques to determine whether each company meets our definition of CDR (see Chapter 1) and, if so, which method it uses (see the Methods Annex). Our cleaned dataset contains 766 CDR companies, 396 of which have at least one recorded investment since 2005. For these companies, 1,260 investors have contributed US$8.4 billion since 2005. Ninety-nine percent of these companies were founded after 2005; six, however, have been operating for at least 20 years but have recently received additional targeted funding to develop new CDR technologies.

The number of CDR companies founded annually peaked in 2022 at 114 and then started to decline in 2023 (see Figure 3.2). However, the steep decline observed in 2024 and 2025 may be due to a data truncation in recent years, since newer and smaller firms are inherently harder to track prior to fundraising or public announcements (see the Methods Annex). At the same time, investor interest in CDR companies appears to be growing. While funding for all climate-tech peaked in 2022 and has continued to decline, funding for CDR rebounded after a dip in 2023 and 2024 to US$1.6 billion in 2025, close to the

US$1.7 billion observed in 2022. Overall, CDR rose from 1.9% of all-climate tech funding in 2022 to 2.6% in 2025.

The diverging trends in CDR startup founding and investment trends may be due to a combination of drivers. First, parts of the CDR innovation ecosystem may be maturing,[78] with private investors shifting to later-stage funding for CDR companies[79] that have less risky business models or active demonstration projects. Second, current market conditions may mean that more CDR innovators prefer to spend resources on technology development (e.g. during the research stage preceding a startup's launch) rather than company organization,[80] resulting in fewer companies founded and more funding for the R&D stage (see Chapter 2). These explanations align with the broader observations in global venture capital markets, including increasing concentration and higher capital costs after 2022 affecting early-stage climate-tech startup formation.[81]

Startup and investor activity across CDR methods also continues to evolve. From 2005 to 2020, 60% of CDR startups founded were afforestation and reforestation or biochar. During this time, all companies developing afforestation and reforestation or biochar methods received a cumulative US$0.35 billion in funding, with 82% of this funding for afforestation and reforestation. Since 2021, DACCS startups have grown rapidly, comprising 13% of new startups. DACCS companies have received US$2.0 billion in funding since 2021, the largest amount across all CDR methods, while afforestation and reforestation companies received US$1.4 billion. Soil carbon sequestration and BECCS form smaller but meaningful shares, receiving US$0.8 billion and US$0.9 billion, respectively, since 2021. Other methods, such as biochar, represent a relatively large percentage of startup formation (34%) but only a small percentage of funding (US$0.5 billion, or 7% of the total US$6.7 billion since 2021).

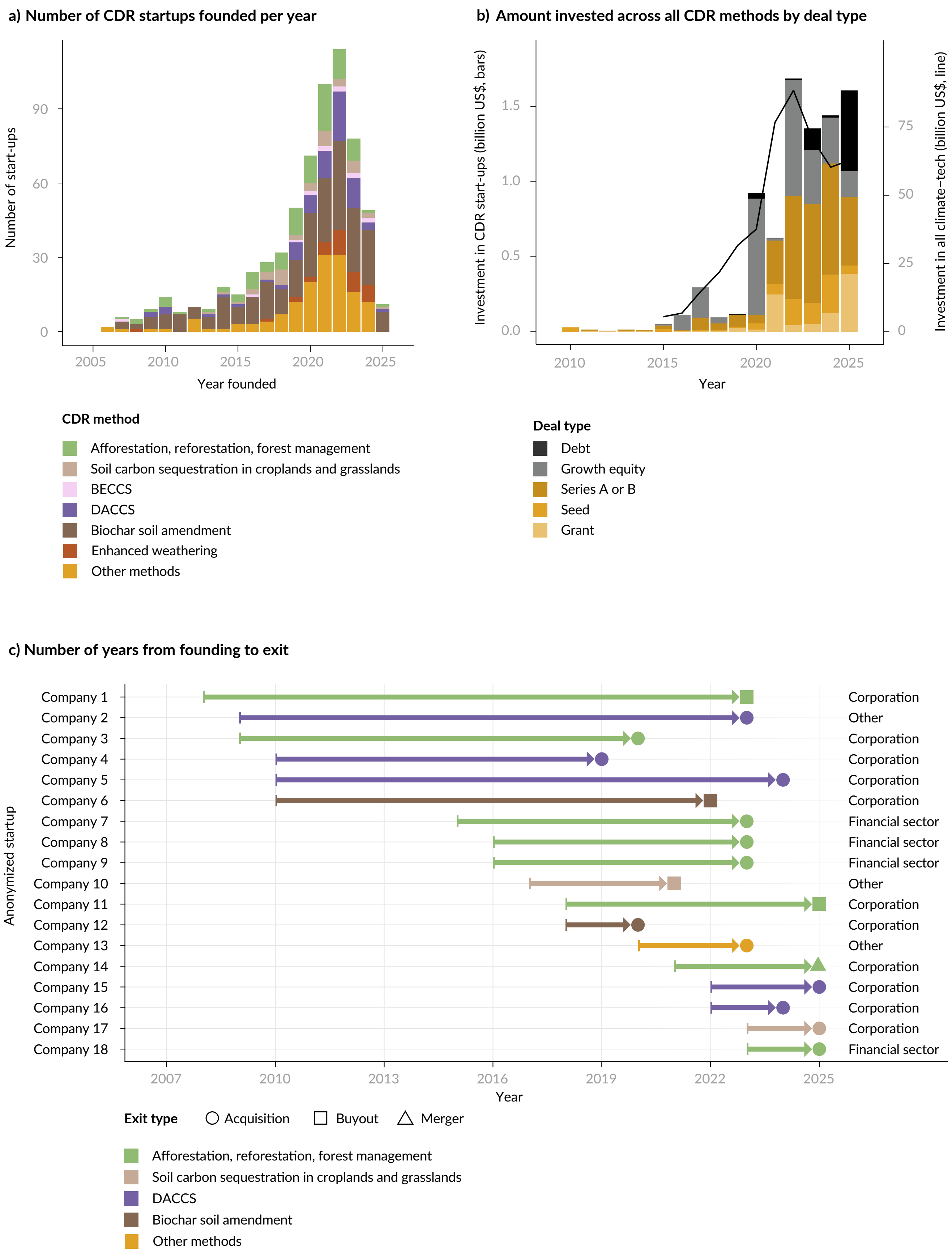
The distribution of funding rounds for CDR companies points to an industry with robust early-stage activity and growing maturity. Overall, a majority of funding is still at an early stage, with 66% of investments from 2024 to 2025 from series A, series B or seed funding, or from grants. Afforestation and reforestation (20%) and DACCS (40%) received the largest shares of this early-stage funding. DACCS and soil carbon sequestration companies received the most growth equity funding since 2024 (34% and 56% of funding, respectively), while in 2025, Stockholm Exergi, an established energy company, financed a new BECCS project with US$0.5 billion of debt. While NZI reports only 18 exits by CDR companies, 13 of these have occurred since 2023. Across all exits, 13 are acquisitions, and 10 of the companies were acquired by corporations. The time between founding to exit ranges from 2 to 15 years but has decreased over time (see Figure 3.2c). These trends point to more CDR activity by established, diversified companies. Overall, funding is highly concentrated, with 72% of investment dollars in 2025 going to four companies.

Funding for CDR comes from a variety of sources (see Figure 3.2d). Venture capital investors participate in 48% of all funding rounds and represent 17% of total investment.

While they participate in few rounds, financial sector investors are the largest source of funding, cumulatively investing US$1.9 billion in CDR companies since 2021 (60% as growth equity). Financial sector investors and public/quasi-public investors together drove a US$730 million (205%) increase in CDR funding from 2024 to 2025; this offset a US$300 million (66%) funding decrease from venture capital and corporate investors during the same period. European and Canadian governments – along with some state-level governments in the United States – drove a surge in public/quasi-public investment in 2025. Federal agencies in the United States, which have previously supported funding efforts, have pulled back. While most investor types diversify across CDR methods, corporate investors appear to have favoured soil carbon sequestration companies before 2021, which received 88% of all corporate investments, and DACCS companies since 2021 (40% of corporate investments).

Our analysis focuses on companies that follow the three principles of CDR as described in Chapter 1, based on an analysis of their descriptions in the NZI database. We account for ambiguity, including companies where storage can be inferred from the capture method (such as afforestation and reforestation) or where no explicit description of point-source capture or utilization is given. In addition to these companies, many companies develop CDR-adjacent technologies; these companies are not purely focused on CDR but develop products that may be useful components of future CDR processes. One example is companies that capture CO_2 but incorporate it into products where it is re-released over the lifetime of the product, such as synthetic transportation fuel. Another is companies that capture CO_2 from point-source combustion of fossil fuels, not the atmosphere. These types of CDR-adjacent companies have together received US$16 billion since 2023. Finally, many companies engage in CDR-enabling activities, specifically financing platforms that connect individual purchases to CDR projects or MRV systems. We track these companies as additional indicators of an evolving CDR ecosystem.

Indicators of upscaling activity and investment trends by CDR startups



d) Cumulative investment flows from investor type to CDR method

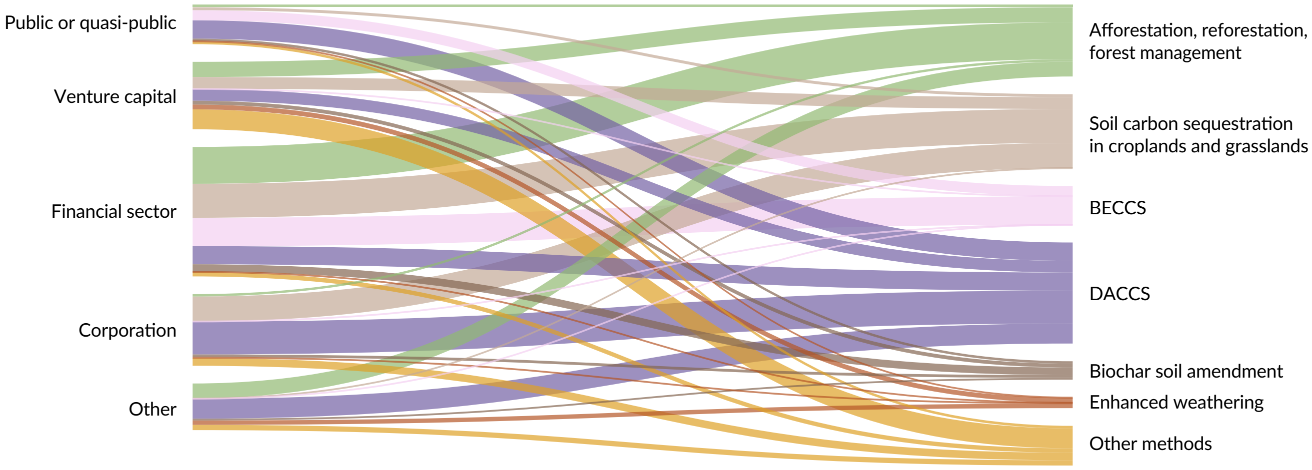


Figure 3.2 *(a) Number of CDR startups founded each year, (b) amount invested across all CDR methods by deal type, (c) number of years from founding to exit for 18 companies, and (d) cumulative investment flows from investor type to CDR method. Data for startups founded in 2024 and 2025 may be heavily truncated (see the Methods Annex). "Other methods" refers to agroforestry, peatland and coastal wetland restoration, mineral products, durable wood products, bio-oil storage, biomass burial, ocean fertilization, biomass sinking, alkalinity enhancement of water bodies and DOCCS.*

Box 3.3 The diverse business models of European CDR startups

Converting leads into actual sales has been identified as a key bottleneck facing CDR startups (see *The State of CDR 2nd Edition*). Challenges including high prices and uncertainties in the voluntary carbon market (VCM), and related to MRV, are driving a fundamental restructuring of how CDR startups operate. Generating and selling credits in the VCM may no longer be the only go-to business model for CDR startups.

A survey conducted by the Sustainability in Business Lab (sus.lab) at ETH Zurich and the CDR accelerator remove explored this shift among 69 European startups.[82] The survey revealed a move towards more diversified business models. Follow-up interviews with 18 startups identified two key factors driving diversification: limited market demand and complex sales processes for CDR credits, and a desire for basic business efficiency. Companies thrive when they concentrate on their core competencies rather than wrestling with the difficulties of VCM sales. Many startups now supplement or replace direct VCM credit sales with alternative business models, especially insetting, and product and asset models. The insetting model monetizes CDR within customers' value chains. For instance, Cotierra collaborates with large coffee retailers to explore insetting within their supply chain by providing biochar solutions to smallholder coffee farmers. The product model involves selling CDR-derived products or services without issuing credits, an approach taken by Reaforma, which produces calcined clay in biomass-powdered kilns. And finally, the asset model consists of selling or licensing technology for use by other organizations, as demonstrated by Captur Tower, which sells DAC installations and provides operation and maintenance services to industries requiring CO_2 as a feedstock.

This shift indicates how the CDR industry is maturing. The trend toward more distinct business-to-business strategies pushes startups to more clearly define customer segments and value propositions, improving operational efficiency and scalability. Adopting multiple, often hybrid, business models appears to be a natural progression for startups seeking to establish themselves in a rapidly evolving market. Successfully navigating these currents requires strategic flexibility and the ability to capitalize on new commercial opportunities while preserving credibility. Startups must balance short-term pragmatic adaptation with long-term positioning to capture value as the market matures. Those who manage this transition effectively are likely to emerge as key players in the evolving CDR ecosystem.

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Box 3.4 Skills and CDR workforce development for deployment and scaling

Building a workforce spanning engineering, operations, project management and other services is essential for scaling CDR from pilots to large-scale deployment. Early signs point to talent availability as a key bottleneck (see *The State of CDR 2nd Edition*). Although global estimates remain scarce, one independent US analysis[83] suggests that scaling durable removals to around 0.1 $GtCO_2$ per year could support 95,000–130,000 jobs annually, illustrating the magnitude of workforce demand even at modest deployment levels. Using data from CDRjobs,[84] we provide a quantitative overview of CDR job postings, categorized by CDR method and skills. CDRjobs is a global database and analytics platform that tracks open positions across CDR companies using company websites and public job boards. The data capture job title, company, CDR method, contract type, location, discipline, experience and education requirements and salary range. We analysed approximately 4,500 full-time listings from over 350 novel CDR and CDR-enabling companies worldwide between April 2024 and December 2025, offering a snapshot of the emerging CDR labour market (see Figure 3.3).

Engineering and technical operations account for the largest share of job postings, highlighting the infrastructure-intensive nature of early CDR scale-up. Novel removal methods like DACCS account for nearly 30% of all postings, with engineering and technical operations accounting for the largest share of DACCS vacancies (45%). Across all openings, a 24% share for CDR ecosystem or enabling services captures the expanding importance of supporting activities, such as MRV providers, certification platforms and project developers for the functioning and credibility of CDR removal. Their prominence underscores how supporting capabilities are becoming as strategically important as removal technologies. Biochar, mineral products and BECCS show more diverse workforce needs, with openings more evenly distributed between the engineering, operations and sales categories. Other methods encompassing emerging pathways – such as ocean-based CDR, biomass sinking, bio-oil storage and durable wood products – account for 24% of all postings.

Although the postings analysed span multiple regions, hiring activity skews towards companies and startups from North America and Europe. This concentration reflects both the high density of early-stage CDR firms in these markets and the greater visibility of recruitment channels in these regions. Consequently, regional hiring in Africa, Latin America and parts of Asia is likely underrepresented, as these regions often rely heavily on localized or offline recruitment practices. Furthermore, the data show a relative underrepresentation of job postings for conventional CDR methods such as afforestation and reforestation and soil carbon sequestration. This likely reflects differences in recruitment practices, as these methods have traditionally relied more on offline and informal hiring channels than online job boards. A more comprehensive outlook would require combining job board analytics with targeted surveys to provide a globally representative picture of the CDR workforce.

Distribution of full-time CDR job postings by skill category

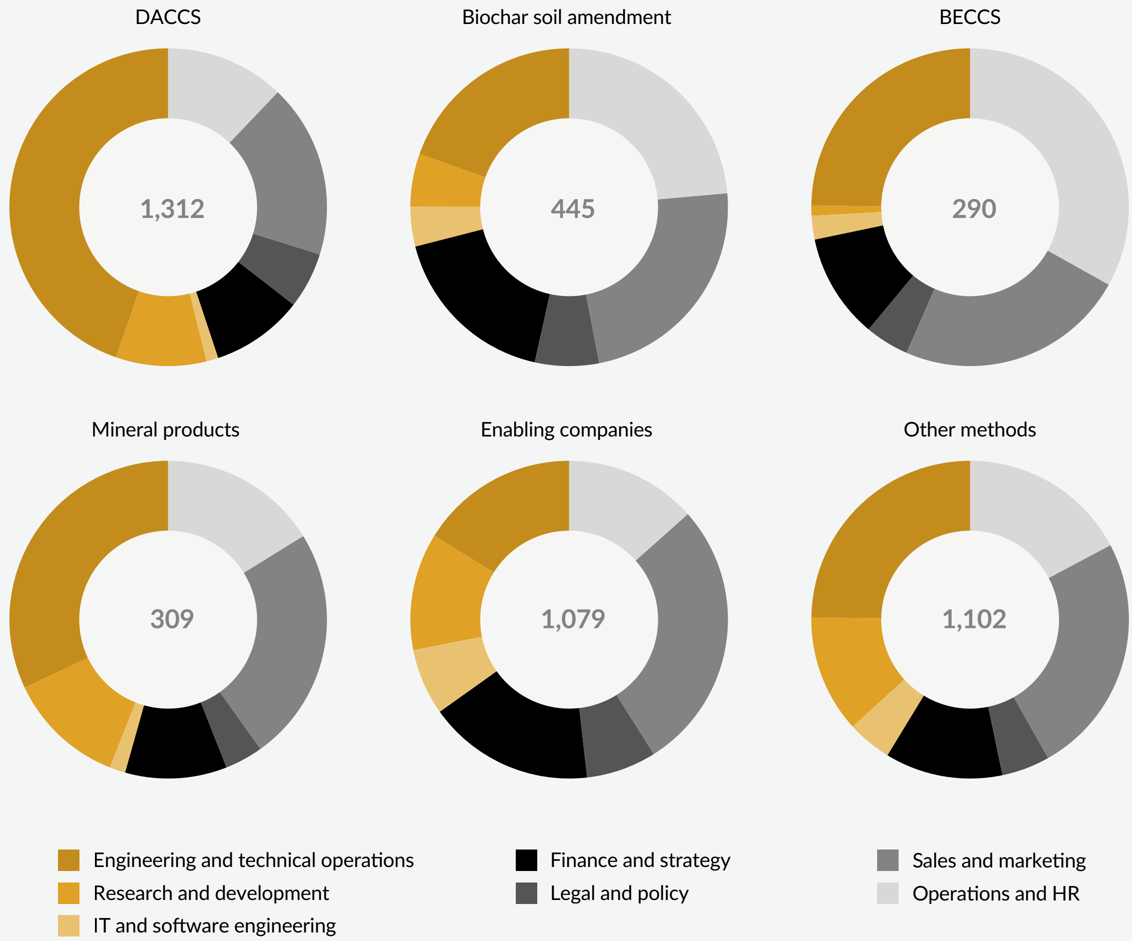

Figure 3.3 *Job postings for CDR and enabling companies from April 2024 to December 2025. Each donut represents a different method, with segments showing the breakdown of job postings across seven workforce categories. Numbers in donut centre indicate total postings per method. Data reflects publicly advertised full-time positions captured in the CDRjobs dataset. Other methods include afforestation, reforestation and forest management, enhanced weathering, DOCCS, ocean fertilization, alkalinity enhancement of water bodies, soil carbon sequestration, bio-oil storage, biomass burial, biomass sinking and durable wood products.*

3.3 Company ambition for novel CDR

Companies have announced their ambitions for novel CDR over the coming decades (from 2030 to 2050). In the near-term, they have also made plans to upscale CDR (see Chapter 7). The credibility of the long-term public announcements in terms of both timelines and scale is uncertain. While Chapter 7 presents projects that are "in the pipeline" between 2025 and 2030 if they are under construction, the removal capacities included in this analysis must only reach the threshold of being announced and are not necessarily tied to specific projects. These announcements do not necessarily indicate whether funding has been acquired for specific projects, whether projects are under construction, or even whether engineering studies have begun. We include them in our analysis if a company has made a public announcement about an ambition that includes both a year and capacity. Company announcement data was gathered through three mechanisms listed below (more details on data gathering can be found in the Methods annex).

1. New for *The State of CDR 3rd Edition*, we developed an industry survey of CDR companies.

2. For all companies that had included a long-term ambition in *The State of CDR 2nd Edition*, we updated their announcement data.

3. We gathered data from companies that received late-round funding or that included a removal goal in their pitch line (see Section 3.2) but were not otherwise included in our dataset.

The total number of individual announcements through these three mechanisms that included adequate details was 52. These add up to the removal of 5.29 $GtCO_2$ per year by 2050 – comprising of 71% from DACCS, 19% from soil carbon sequestration in croplands and grasslands, 10% from biochar and less than 1% from other methods. Since *The State of CDR 2nd Edition*, ten companies that previously reported a long-term ambition no longer report it. Some removed the announcement from their website, some include a capacity without a year, some cancelled projects, and others only made the announcement in a report and have neither repeated nor updated it since. In addition, five companies have either pushed their ambition further into the future or have lowered their capacity goal from a previous announcement. Despite these changes, the cumulative novel CO_2 removal that companies have announced between 2030 and 2050 exceeds the median amount of novel CO_2 removal in the scenarios considered in Chapter 8. Whether companies will reach these ambitions is uncertain.

Company ambitions of novel CDR capacity, 2030–2050

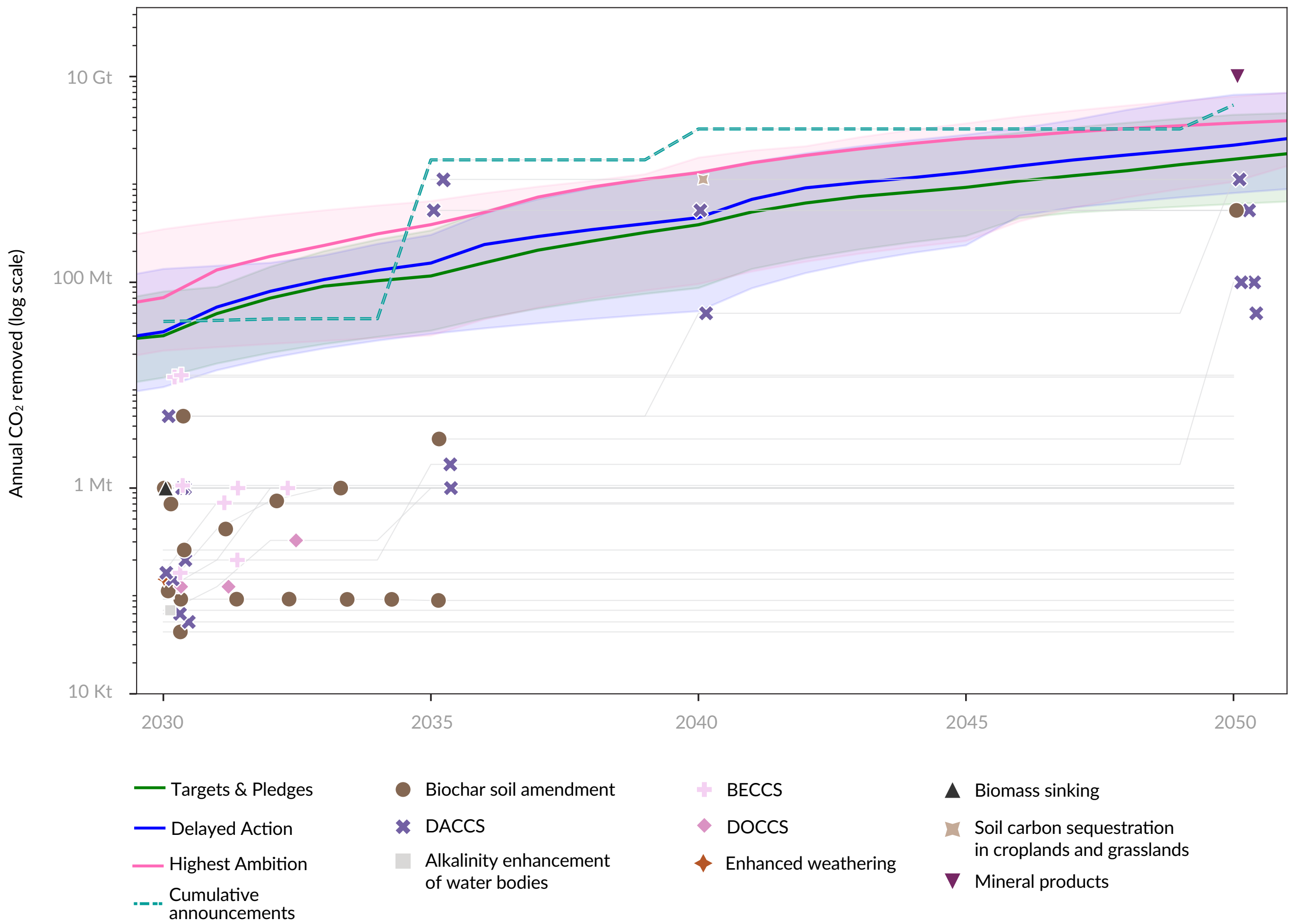

Figure 3.4 *Novel CDR capacity ambitions reported by companies. The dashed line shows the cumulative capacity of company ambition; points are individual announcements of company ambitions; each faint grey line is a time series for one company; solid lines show the median amount of novel CDR in three scenario pathways (Targets & Pledges, Delayed Action and Highest Ambition; see Chapter 8). The shaded areas around the solid lines show the minimum and maximum values. Company ambitions are not filtered by their project status or completion, so whether these announcements will be reached is highly uncertain. One company target point, the 2050 mineral products point, is not included in the total because the company ambition may be an industry-wide ambition – although it is unclear.*

As of the end of 2025, 2.0 million tonnes of CO_2 have been delivered from novel CDR methods (see Chapter 7). Twenty-two companies have a capacity announcement for 2030, totalling 42 million tonnes. Using current deployment figures as a base, reaching the 2030 announcements would require a compound annual growth rate of 84%. Expanding from the 2.0 million tonnes of deployed capacity in 2025 to the 2050 announced capacity of 5.29 billion tonnes would require a compound annual growth rate of 37%. For context, the global cumulative capacity of solar photovoltaics grew at a compound annual growth rate of 36% per year between 1975 and 2018, and the number of electric vehicles in use globally grew at a compound annual growth rate of 80% per year between 2005 and 2019. Reaching the amount of novel CDR implied by long-term company ambitions will require similarly fast growth. The characteristics of both a particular technology and the country in which it is adopted can impact the speed of technological growth; a stable policy landscape, for instance, can support such growth. Moreover, novel CDR approaches differ from solar photovoltaics and electric vehicles in many ways that may impact growth. Nevertheless, these historical examples provide interesting studies in rapid technological growth (see Box 3.5 for additional comparisons).

Generally, we see less ambitious longer-term company announcements in this edition than in *The State of CDR 2nd Edition*. In the 2nd Edition, long-term company announcements totalled 11 $GtCO_2$ removed per year, including one announced ambition of 8 $GtCO_2$ per year by 2050. That announcement is no longer included in the 3rd Edition dataset, as it has been removed from the company's website. In the 3rd Edition, total company ambition is 6 $GtCO_2$ removed per year less than in the previous edition. However, if we exclude the most ambitious company in the previous dataset, the total ambition in this edition is 2 $GtCO_2$ removed per year greater.

Company ambitions are highly variable over time; some companies make new, ambitious announcements, while other companies that previously announced large ambitions later remove them from public view. Because company ambitions are not necessarily tied to specific projects, it is difficult to interpret why ambitions change at an industry scale. Companies that have lowered or removed their long-term ambitions may be moving to a more mature phase of development, responding to more realistic long-term plans, or a shifting in focus from setting ambitions to building CDR capacity. On the other hand, a rise in more ambitious announcements may indicate confidence in the CDR market.

Box 3.5: Historical technologies show the urgency of upscaling CDR

Technology innovation takes time, and so does widespread adoption. Figure 3.5a shows 111 examples of technology scale-up. The scale-up curves show the values from fitting a logistic function onto technology adoption time series data, scaled to the first year of commercialization for each technology (x-axis) and scaled to the asymptote value derived from the logistic function fit (y-axis). The speed and scale reached in the first 25 years of the time series varies considerably across technologies. Three examples are highlighted in the figure to demonstrate a slower- (hydroelectricity), medium- (cell phones), and faster-paced (vehicle disk brakes) diffusion pathway. These diverse pathways demonstrate that there are many possibilities for the future of novel CDR scale-up.

Historical speed and scale of technology diffusion

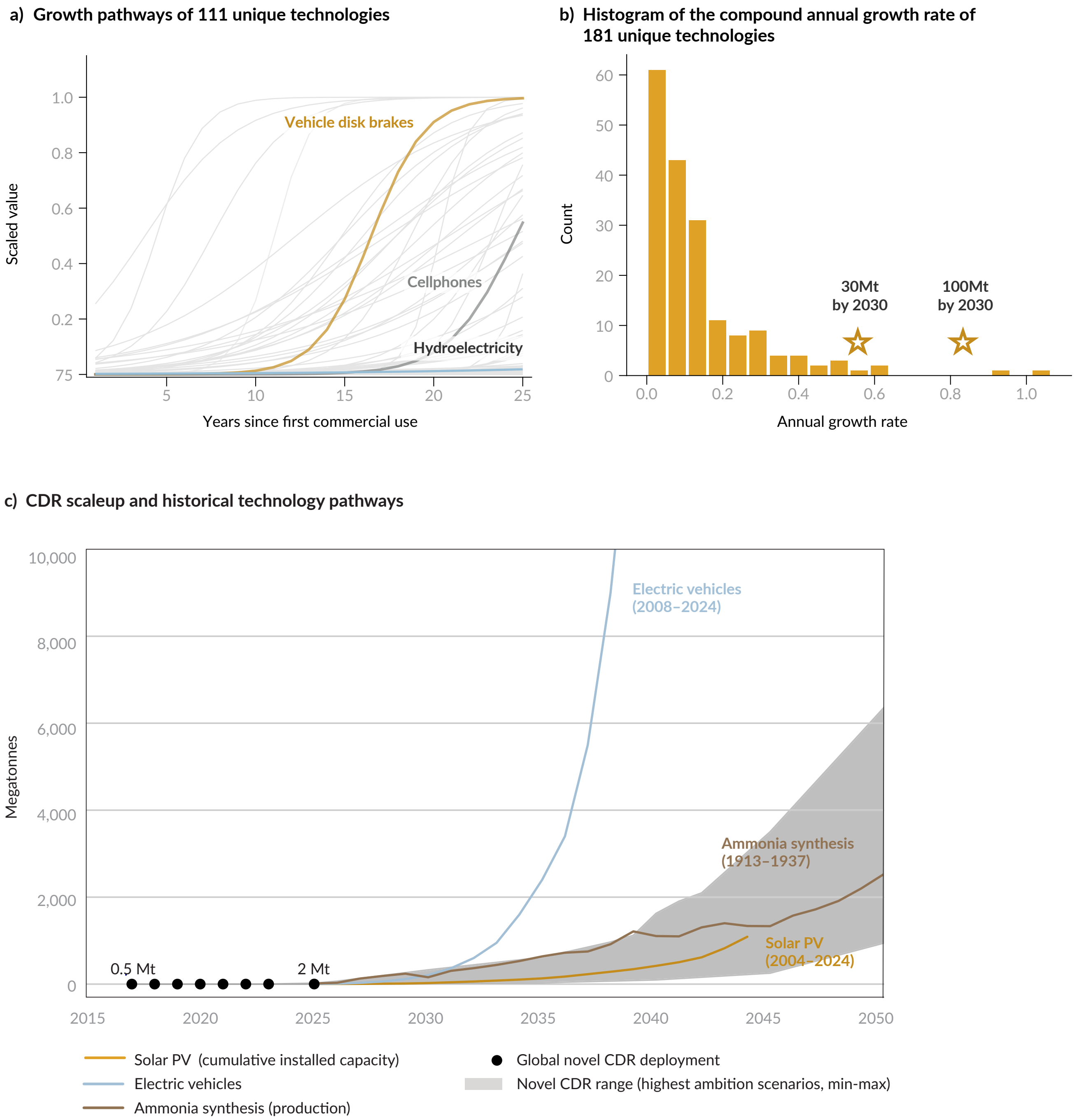

Figure 3.5 *(a) The growth pathways of 111 unique technologies, with three technologies highlighted to show examples of a fast, medium and slow diffusion pathway in the 25 years after first commercialization, (b) a histogram of the compound annual growth rate of 181 unique technologies compared to goals for novel CDR scale-up, and (c) pathways of novel CDR if it follows the growth trajectories of three example technologies compared to the highest ambition scenarios (see Chapter 8).*

Two 2030 goals for the scale-up of novel CDR have been proposed recently, both of which focus on international collaboration to catalyse growth. An independent review of GHG removals commissioned by the UK Department for Energy Security and Net Zero[85] proposes a global "30 by 30" campaign as part of its recommendation to pursue international collaboration efforts. The proposed campaign would focus on building 30 million tonnes of operational CDR capacity globally by 2030. Meanwhile, at COP 30 in 2025, CDR2030[86] – a new initiative under the UN Climate High-Level Champions architecture – launched the CDR Mutirão, a collaboration to accelerate progress towards reaching 100 $MtCO_2$ of novel removal capacity and 3 $GtCO_2$ of conventional carbon removal capacity by 2030. The Mission Innovation CDR Mission[87] has a similar goal for novel CDR scale-up.

Both of the 2030 targets represent potential scale-up pathways for novel CDR that may benefit from comparison to historical technology scale-up. Reaching 30 $MtCO_2$ of novel CDR by 2030 from 1.3 $MtCO_2$ of novel CDR in 2023 implies a compound annual growth rate of 57%. When compared to 181 historical examples of global technology growth, this rate is on the fast end of the spectrum (see Figure 3.5.b). There is some precedence for this growth speed in other technologies: magnetic data storage, cell phones, lithium-ion battery storage and internet traffic have all grown faster than the implied compound annual growth rate for novel CDR. By comparison, reaching 100 $MtCO_2$ of novel CDR by 2030 is more ambitious and implies a compound annual growth rate of 86%. Lithium-ion battery storage and internet traffic both scaled faster than 86%. Since novel CDR refers to a portfolio of diverse methods, a one-to-one comparison with the individual technologies assessed in Figure 3.5 is not straightforward. However, this analysis illustrates that although both the novel CDR goals are ambitious, the speed of upscaling is not unprecedented when compared to other transformative technologies.

Box 3.6 Limitations and knowledge gaps

- Demonstration projects reported in Section 3.1 have either been announced, are under construction or are in operation. Some of these demonstration projects may have been cancelled, but that information is not always available. Companies tend only to announce celebratory milestones and do not typically offer project status updates, so some projects included in Section 3.1 may in reality have been delayed or mothballed. IEA and Mission Innovation are improving their methods for monitoring project status and providing updates, which would improve the accessibility and robustness of their databases going forward.

- The analysed demonstration programmes and projects are concentrated in geographic areas where data has been made available, for instance through the Clean Energy Ministerial and Mission Innovation. Not all countries are parties to these groups, so any CDR demonstration projects or public programmes to support CDR demonstration projects in these countries may not be included, despite our efforts to collect comprehensive data. In the future, wider research may provide a more complete picture of demonstration projects globally.

- NZI uses a combination of public data scraping and individual submissions to record investments and categorize companies under its hierarchy of climate solutions. This approach may not record all investments or categorize all climate-tech startups accurately, especially for startups reporting activities in languages other than English and located outside of the United States and Europe. Additionally, while compiling funding data for startups is a useful metric for tracking innovation, it does not capture privately supported innovation within corporations or private research institutions. Future work could compare funding reported by NZI to other indicators of innovation such as patents (see Chapter 2).

- CDRjobs tracks publicly advertised vacancies and individual submissions, an approach which may underrepresent hiring through networks, accelerators and academic partnerships common in early-stage startups. The dataset could, therefore, be biased towards mature companies and firms in the United States and Europe. In addition, the data include few postings for conventional CDR such as afforestation, reforestation and forest management or soil carbon sequestration in croplands and grasslands; this may reflect differences in recruitment practices across the CDR methods, with conventional pathways often relying more on offline hiring than online job boards. Moreover, regional hiring in Africa, Latin America and parts of Asia, where offline recruitment is common, may be underrepresented. Future updates could track the evolution of the CDR workforce over time and expand data coverage in underrepresented regions (for example by incorporating employer surveys).

3.4 Outlook

Across this analysis, we find evidence of an increasingly mature CDR ecosystem. More countries are using diverse policy mechanisms to fund CDR demonstration projects. More CDR startups are receiving late-stage investment, while fewer startups are being founded. Long-term company ambition, assessed through company announcements, is less ambitious than in the previous edition – but with changes in the set of companies that have adopted long-term ambitions. This may signal that some companies have strategically refocused away from announcing long-term ambition and towards focusing on building capacity. Workforce development is also expanding beyond engineering and technical roles to encompass more enabling services, reflecting the growing needs of the CDR ecosystem to support scale-up. These findings may suggest that more CDR innovators are focusing on meeting reasonable growth benchmarks with tested CDR methods, refining novel methods in the research and development stages before soliciting support for late-stage growth.

At the same time, significant challenges threaten the pace and stability of CDR upscaling. Funding for demonstration projects currently depends heavily on institutional continuity, which remains fragile. While more countries are funding CDR demonstration projects, policy reversals, particularly in major markets like the United States, underscore that funding uncertainty remains a key barrier to demonstration projects and continued growth of the CDR ecosystem. Furthermore, many companies continue to struggle with the persistent bottleneck of converting leads into actual sales due to the uncertainty in the VCM (see Chapter 4), as evidenced by the shift among European startups towards alternative business models.

Increasing support for demonstration projects – and investment in CDR companies across the value chain – will be essential to bridge the gap between current levels and future ambition. Ultimately, delivering on announcements from CDR innovators for removals in 2030 and beyond – whether at the company scale or through coordinated efforts such as CDR2030 – will require rapid growth that, while not unprecedented, necessitates sustained effort and public and private support.

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Chapter 4

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A sapling plantation drive for agroforestry near Kanha National Park in Madhya Pradesh, India. By Aaran Patel

Chapter 4 | Voluntary demand for CDR

Voluntary demand for CDR helps to finance CDR projects. Despite the overall market share remaining small, both novel and conventional CDR have experienced strong growth, especially when compared to the reduction and avoidance parts of the VCM. Voluntary buyers are propelling most of the current demand for novel CDR, but compliance markets have the potential to become a source of demand over the long term.

Key insights

- Novel CDR issuances are growing much faster – over 100% year-over-year – than conventional CDR, though both still account for a relatively small share of credit issuances and retirements on the VCM.
- Novel CDR credits are structurally distinct from avoidance and conventional CDR credits and so do not tend to face the same types of additionality and permanence challenges. However, evidence of real-world performance remains nascent for many methods, and significant scientific uncertainties and MRV challenges persist.
- CDR deployment in the VCM is regionally concentrated. Latin America and the Caribbean host 47% of all CDR credit projects and 74% of conventional credit projects, while Europe leads in novel CDR credits, hosting 48% of all novel credit projects.
- Demand remains highly concentrated among a small number of voluntary buyers – a critical vulnerability for the ecosystem. Microsoft alone purchased over 80% of the novel CDR credits in 2024–2025.
- Emerging sources of voluntary demand, including Article 6 of the Paris Agreement and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), are unlikely to provide substantial new sources of offtake, given their lower average market prices relative to most CDR credits. This suggests the importance of additional, mandatory sources of demand coming online in future.

CDR has been part of the VCM since its inception, yet it has remained a relatively small component. The transaction volume of conventional CDR far exceeds that of novel methods. This largely is due to their longer development history, which stretches back to the Clean Development Mechanism (CDM) in the 2000s. More recently, growing concerns about the environmental integrity of offsetting based on credits with weaker additionality or permanence guarantees, alongside questions of net-zero alignment, have driven increased focus on CDR, particularly novel pathways.[1] This shift has spurred significant growth in voluntary market activity for CDR, accompanied by the emergence of specialist standards and registries to meet rising demand. This chapter unpacks the role of voluntary demand in scaling up CDR and examines trends in voluntary demand, including the size and composition of the market, drawing on multiple datasets to map trends in project types, volumes and buyers.

4.1 The role of voluntary demand in developing CDR

Demand for carbon removal has principally been facilitated via the VCM, which is present both internationally and in a range of domestic settings. The VCM can be conceived expansively as an ecosystem through which projects that avoid or reduce GHG emissions, or remove CO_2, are financed. As such, it includes traditional over-the-counter transactions of carbon credits, as well as various forms of bilateral offtakes. Markets facilitated by the United Nations could also support voluntary CDR demand. This includes markets under Article 6 of the Paris Agreement, which facilitates cross-border financing of mitigation, as well as CORSIA, which allows airlines to offset part of their emissions from international flights. While these examples are established under formal international agreements, participation by private entities to surrender credits under them remains voluntary. For example, airlines may choose to reduce emissions directly rather than purchase CORSIA Eligible Emissions Units. This serves as a contrast to compliance mechanisms where participation is mandatory within a given national or subnational context (see Chapter 5). Despite these forms of markets having distinct hallmarks, in practice they often constitute a blend of increasingly interrelated mechanisms (see Box 4.1).

Box 4.1 The evolution of carbon markets facilitating voluntary demand for CDR

While the carbon market landscape has evolved significantly over the past four decades, CDR has been present since its inception, and markets have proven an important conduit for voluntary investments into CDR credit projects.

Project-based trading of environmental attribute certificates emerged in 1982, when the US Environmental Protection Agency authorized refiners to engage in inter-refinery trading of lead credits, enabling them to meet mandated reductions in an economically efficient manner. The first VCM project was a removal-based agroforestry venture in Guatemala in 1989. From this foundation, the Kyoto Protocol catalysed the first generation of carbon markets under the United Nations through the CDM and Joint Implementation (JI), which became operational in the 2000s. The CDM marked the first large-scale attempt to channel finance towards project-based mitigation activities; this produced Certified Emission Reductions (CERs) each representing 1 tCO_2e in reduced or avoided emissions or removals. Importantly, the CDM only enabled conventional CDR to register temporary CERs rather than the permanent credits issued through other types of activities. The project-based CDM was later linked to some allowance-based compliance carbon markets, such as the EU ETS, becoming a further source of demand for credits. Integration between these markets was later suspended due to environmental integrity concerns, with close to one billion CER units having entered the EU ETS; this deflated prices and weakened the abatement signal.[2] In parallel with the CDM, the first generation of the VCM continued to take shape, borrowing methodologies and approaches from the CDM but primarily serving corporate social responsibility goals rather than regulatory objectives. The VCM did not adopt the temporary crediting format from UN markets, issuing carbon credits for conventional CDR projects of equivalence to ones from non-CDR activities.

A second generation of carbon markets began in 2015 with the Paris Agreement and the introduction of carbon trading under Article 6 via cooperative approaches (Article 6.2) and the Paris Agreement Crediting Mechanism (PACM) (Article 6.4). These support the exchange of Internationally Transferred Mitigation Outcomes (ITMOs) as well as mitigation contribution units, both also measured in tonnes of CO_2e reduced or removed.[3, i] In this way, Article 6 has ushered in a new generation of UN carbon markets connected to international sectoral markets, such as CORSIA, as well as the broader second-generation VCM and its associated heightened focus on integrity of supply. These links signify a growing harmonization of standards and recognition of VCM credits within regulated and semi-regulated frameworks and have helped to facilitate the flurry of demand that came in the wake of net-zero commitments from 2018 onwards.

i While relevant UNFCCC decisions formally exclude "avoided emissions", they include forms of reducing emissions from deforestation and forest degradation in developing countries projects that are understood in the VCM as avoided emissions emission projects, including some forms of (REDD+). See Johnstone, I. Article 6 in focus: Bottlenecks and breakthroughs at Bonn 2024. https://www.smithschool.ox.ac.uk/news/article-6-focus-bottlenecks-and-breakthroughs-bonn-2024 (2024).

The current trajectory suggests a future where voluntary, UN and compliance markets are increasingly interoperable (see Chapter 5). In this sense, a third generation of carbon markets, which could facilitate seamless transactions across these three domains, could be emerging. Although these links remain speculative, the inclusion of cross-border CDR within future stages of ETS schemes could result in a project using a VCM methodology to produce ITMOs under Article 6.2 that are ultimately surrendered by a covered entity for compliance purposes. This evolving ecosystem reflects a gradual convergence of markets once seen as siloed. This is enabled by new standards, transparency requirements and governance frameworks that reflect lessons learned from earlier generations of market mechanisms.

Examples of carbon markets facilitating demand for CDR

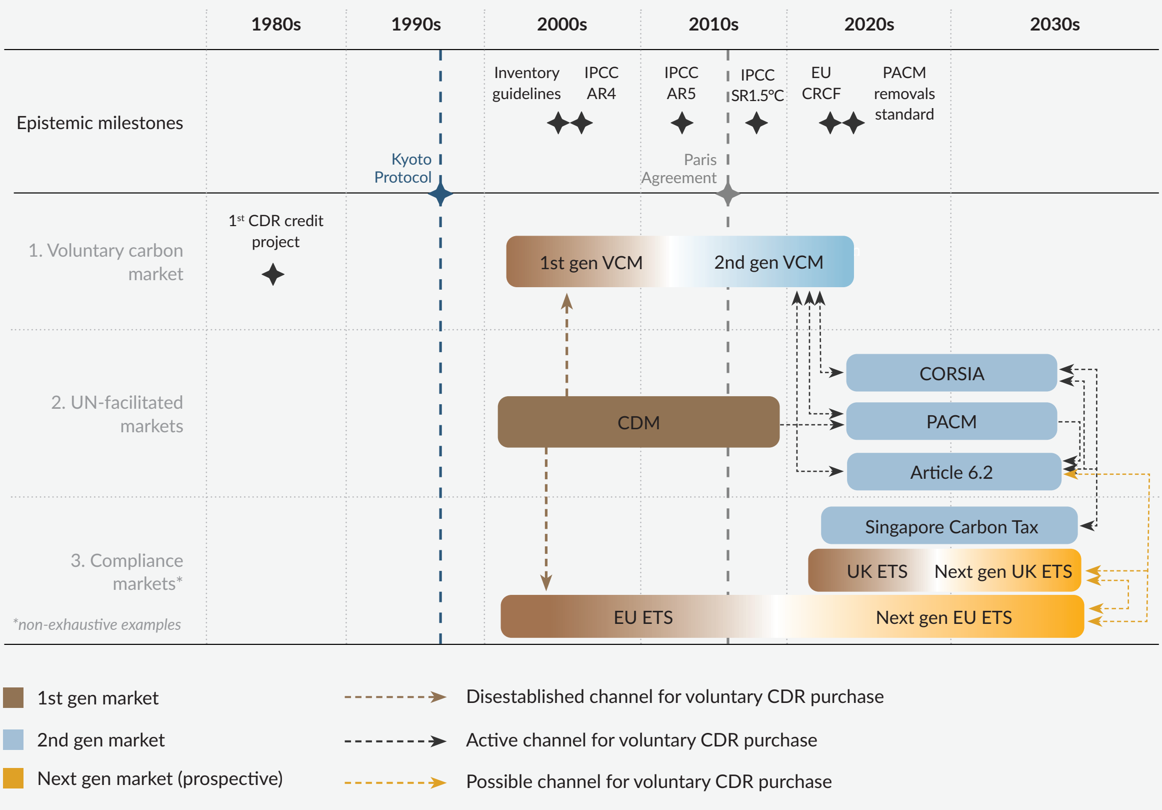


Figure 4.1 *Examples of carbon markets facilitating demand for CDR. Milestones indicate both epistemic and diplomatic milestones. Arrows indicate the connectivity between markets that is either one way (single arrow) or bi-directional (double-headed arrow). Note while over 80 compliance markets exist today, the ones profiled are chosen to show either integration between each other and of CDR specifically (EU and UK ETS) and/or existing compliance regimes that already integrate Article 6.*

Markets that trade in CDR also enable trade in other project types. A key distinction – crucial for evaluating the durability and integrity of credits – is between projects that reduce or avoid emissions and projects that actively remove carbon from the atmosphere.[4] Projects that reduce or avoid emissions include forest conservation and clean cookstoves. Removal projects may be novel, such as DACCS, where carbon is sequestered for millennia, or conventional, such as afforestation, where stored carbon may be rereleased over time due to fire or land-use changes. Some methodologies, however, involve both removal and avoidance. Following the approach of *The State of CDR 2nd Edition*, this chapter classifies carbon projects according to the methodology they employ to generate credits (see Table 4.1).

Classification of projects by methodology

Project type	Methodological description	Examples
Emissions reductions	Activities that reduce emissions relative to an observed baseline	Renewable energy, cookstoves
Avoided emissions	Activities that avoid emissions that would occur under a counterfactual scenario	Avoided grassland conversion, avoided deforestation (REDD+)
Mixed (mainly avoided)	Activities that both avoid emissions and remove carbon, but primarily avoid emissions	Most forms of improved forest management, sustainable agriculture
Mixed (mainly CDR)	Activities that both avoid emissions and remove carbon, but primarily remove carbon	Sustainable grassland management, peatland restoration, some forms of improved forest management
Conventional CDR	Activities that remove carbon through land-based management of carbon stocks	Afforestation and reforestation, some forms of improved forest management
Novel CDR	Activities at lower readiness levels that remove carbon and durably store it, usually in geological formations, the ocean or products	Biochar, DACCS, BECCS

Table 4.1 *Note: Section 4.2.1 of the Technical Annex provides a detailed list of how projects are mapped to the project classes.*

To assess the state of carbon market financing for CDR, we combine several sources to provide an overview of the current structure and dynamics of voluntary demand for CDR, including:

- OffsetsDB, which covers credit issuance and retirements across five main registries, including emission reductions, avoidance and conventional CDR;
- CDR.fyi, which tracks forward contracts, prices and deliveries of novel CDR; and
- nbs.CDR.fyi, which tracks forward contracts of conventional CDR.

While these sources provide broad coverage of voluntary market activity, they are limited to the tracked registries and do not capture all existing crediting systems, including emerging national or domestic standards.

4.2 Voluntary demand for CDR across carbon markets

Market composition

Emissions reduction projects continue to dominate the market, both in terms of credit volumes (see Figure 4.2a) and numbers of projects (see Figure 4.2b). From 2024 to 2025, they accounted for 72.1% of issued credits and 63.4% of retired credits, while representing 79.3% of all active projects. Active projects are those that either issued or retired credits in at least one of those years; projects with forward contracts but no issued or retired credits are excluded. Avoided emissions (including purely avoided and mainly avoided) is the second-largest project class by credit volumes and number of active projects. Avoided emissions projects account for 10.9% of issued credits and 25.0% of retired credits, while mixed (mainly avoided) projects also account for 10.9% of issued credits but only 4.2% of retired credits. Together, these categories represent 8.2% of all active projects, but they account for a disproportionately large share of credit volumes – suggesting larger average project sizes. CDR-based projects make up a significantly smaller share of the market. Conventional CDR projects (2.9% of projects) and mixed (mainly CDR) projects (4.7%) together represent 7.6% of active projects. Conventional CDR projects account for 2.8% of issued credits and 4.3% of retired credits, while mixed (mainly CDR) projects account for 3.0% of issued credits and 2.8% of retired credits. Finally, novel CDR projects account for 4.9% of all active projects on the VCM, but only 0.3% of issued credits and 0.3% of retired credits, reflecting the early-stage nature of many novel CDR approaches.

VCM market activity by project class, 2024–2025

a) Volume of credits issued and retired (millions)

Project Class	Year	Issued credits	Share of issuances (%)	Retired credits	Share of retirements (%)
Emissions reductions	2024	216		105	
	2025	191	72.1%	102	63.4%
Avoided emissions	2024	21		46	
	2025	41	10.9%	35	25.0%
Mixed (mainly avoided)	2024	26		5	
	2025	36	10.9%	9	4.2%
Mixed (mainly CDR)	2024	9		4	
	2025	8	3.0%	5	2.8%
Conventional CDR	2024	7		8	
	2025	8	2.8%	5	4.3%
Novel CDR	2024	0.6		0.3	
	2025	1	0.3%	0.6	0.3%

b) Proportion of active projects in the VCM

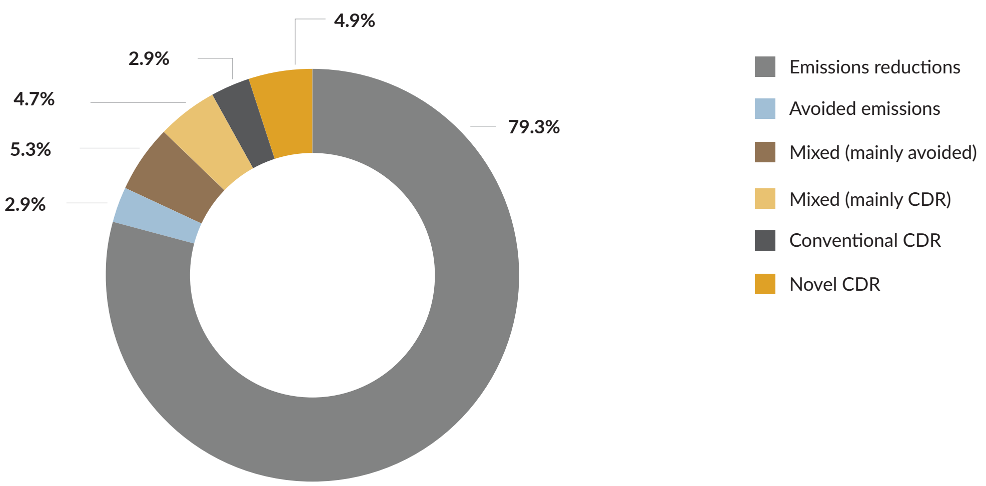


Figure 4.2 *Composition of the VCM across the six project types described in Table 4.1 by (a) the volume of credits issued and retired and (b) the proportion of projects active within the VCM in 2024–2025, by project type (see Technical Annex 4.2.1).*

While nascent, a distinctive pipeline of projects is emerging under the Article 6 framework of the Paris Agreement that could provide a further source of voluntary demand as countries and corporates use it to meet their climate targets. Determining the volume of CDR developed via the emergent Article 6 regime is a more complex picture given its role connecting compliance markets and the VCM to international sources of demand such as CORSIA. Article 6.2 could lead to the development of CDR-focused transactions but does not yet have a formal, CDR-based cooperative approach registered – despite a joint pilot between Norway and Switzerland to test the Article 6.2 infrastructure with a novel CDR transaction.[5,6]

The Article 6.4 PACM project pipeline has a higher number of CDR projects in play. These come from both a transfer of activities from the CDM as well as new projects that have submitted initial notifications under the PACM. As of January 2026, the UN Environment Programme-Copenhagen Climate Change Centre pipeline showed that 2,462 projects and programmes of activities had applied for transition from the CDM into the PACM, 12 of which were conventional CDR.[6] None of those 12 have been approved by the host country to transition.[6] Under the list of activities that have expressed prior consideration to be issued under the PACM standard, 72 out of 1,112 projects are CDR projects. The majority (68 total) are conventional CDR projects, and the minority (4 total) are novel CDR, respectively representing up to 7.7% and 0.0065% of potential future annual Article 6.4 Emission Reductions issuance via this route.[6]

The monetary size of the market

Looking at the market value of the different carbon credit types provides a very different picture from the volume data. Reliable whole-market estimates are difficult to produce: prices vary widely across methods, and most novel CDR transactions remain undisclosed. But even on conservative price assumptions, the dollar value of contracted novel CDR substantially exceeds that of conventional CDR, and the gap widened sharply in 2025 alongside the surge in novel contracted volumes.

Retired volumes tell a different story. Conventional CDR dominates in dollar terms, because much of the novel CDR market remains forward-committed rather than delivered. For context, the total reported value of the voluntary carbon market was US$535 million in 2024[7]; the forward-contracted value of novel CDR very likely exceeds this several times over.

Table 4.2 summarizes the estimated volume of CDR credits transacted on the VCM in 2024 and 2025, separating conventional and novel approaches. It shows that the VCM still facilitates much more conventional CDR than novel CDR at present. However, there is significant growth in both purchase and issuance volumes of novel CDR credits, as large purchases by big enterprises continue to contribute to forward demand and as more novel CDR credit projects move from the pilot to the commercial phase or expand operational capacity to fulfil that demand.

Estimation of CDR volumes in the VCM, 2024–2025

Project Type	Year	Contracted credits	Issued credits	Retired credits
All conventional CDR	2024	21,120,308	16,064,733	12,737,438
	2025	12,968,007	16,492,317	10,372,711
Afforestation, reforestation, forest management	2024	21,120,308	14,409,515	10,072,834
	2025	12,968,007	15,374,683	7,985,205
Soil carbon sequestration in croplands and grasslands	2024	0	0	1,332,381
	2025	0	1,039,245	1,125,358
Peatland and coastal wetland restoration	2024	0	1,655,218	1,332,223
	2025	0	78,389	1,262,148
All novel CDR	2024	8,173,080	620,752	320,841
	2025	30,215,409	1,249,194	628,104
BECCS	2024	5,092,871	157,592	54,276
	2025	20,819,157	363,142	243,921
Biochar soil amendment	2024	1,123,648	388,821	242,339
	2025	2,964,559	793,796	339,431
Bio-oil storage	2024	290,995	10,728	3,650
	2025	5,215,296	37,031	12,090
DACCS	2024	842,707	953	856
	2025	238,453	848	500
Enhanced weathering	2024	365,248	1,370	1,135
	2025	197,957	19,804	12,956
Mineral products	2024	102,023	55,978	13,972
	2025	353,499	14,149	13,677
Biomass sinking	2024	201,223	1,044	1,044
	2025	200,001	526	0
Alkalinity enhancement of water bodies	2024	139,787	0	0
	2025	117,641	3,323	1,649
Biomass burial	2024	11,948	4,266	3,569
	2025	71,100	16,575	3,880
DOCCS	2024	2,630	0	0
	2025	37,746	0	0

Table 4.2 *Notes: Volume of CDR credits on the VCM by method. "Contracted" refers to pre-market activity, where credits are contracted before the underlying carbon removal occurs. "Issued" corresponds to on-market activity, where verified credits are issued and traded. "Retired" refers to off-market activity, when credits are permanently taken out of circulation and used for climate claims. The CDR volumes (in tonnes) include transactions tracked by OffsetsDB and CDR.fyi from projects classified as conventional CDR, novel CDR, as well as mixed (mainly CDR), based on their respective project activities.*

Afforestation, reforestation and forest management dominate conventional CDR activity across all transaction types. These projects accounted for the bulk of issued credits in both 2024 (14.4 $MtCO_2e$) and 2025 (15.4 $MtCO_2e$) and a majority of retirements (10.1 $MtCO_2e$ in 2024 and 8.0 $MtCO_2e$ in 2025). Peatland and coastal wetland restoration – along with soil carbon sequestration in croplands and grasslands – contributed comparatively modest volumes, generally in the low millions or below one $MtCO_2e$ per year. Total contracted volumes for conventional CDR reached 21.1 $MtCO_2e$ in 2024 and 13.0 $MtCO_2e$ in 2025.

Novel CDR shows a different pattern. In 2025, contracted volumes of novel CDR amount to 30.2 M tCO_2e, an almost four-fold increase from 2024, for the first time overtaking contracted volumes of conventional CDR. Contracted volumes are dominated by BECCS, with more than 5.1 $MtCO_2e$ contracted in 2024 and a sharp increase to 20.8 $MtCO_2e$ in 2025. BECCS is followed by bio-oil storage and biochar projects in terms of contracted credit volumes. Delivered and retired volumes, however, are led by biochar. Biochar issuances reached 388,821 tCO_2e in 2024 and 793,796 tCO_2e in 2025, with retirements of 242,339 tCO_2e in 2024 and 339,441 tCO_2e in 2025. Other novel pathways – mineral products, bio-oil storage, enhanced weathering, DACCS, alkalinity enhancement and biomass sinking – contributed much smaller volumes overall, typically in the tens of thousands of tonnes or less. Importantly, most novel CDR credits remain ex ante, meaning the underlying removal activity will occur in the future, while conventional issuances and retirements reflect ex post, verified removals.

Geographic distribution of voluntary CDR credit projects

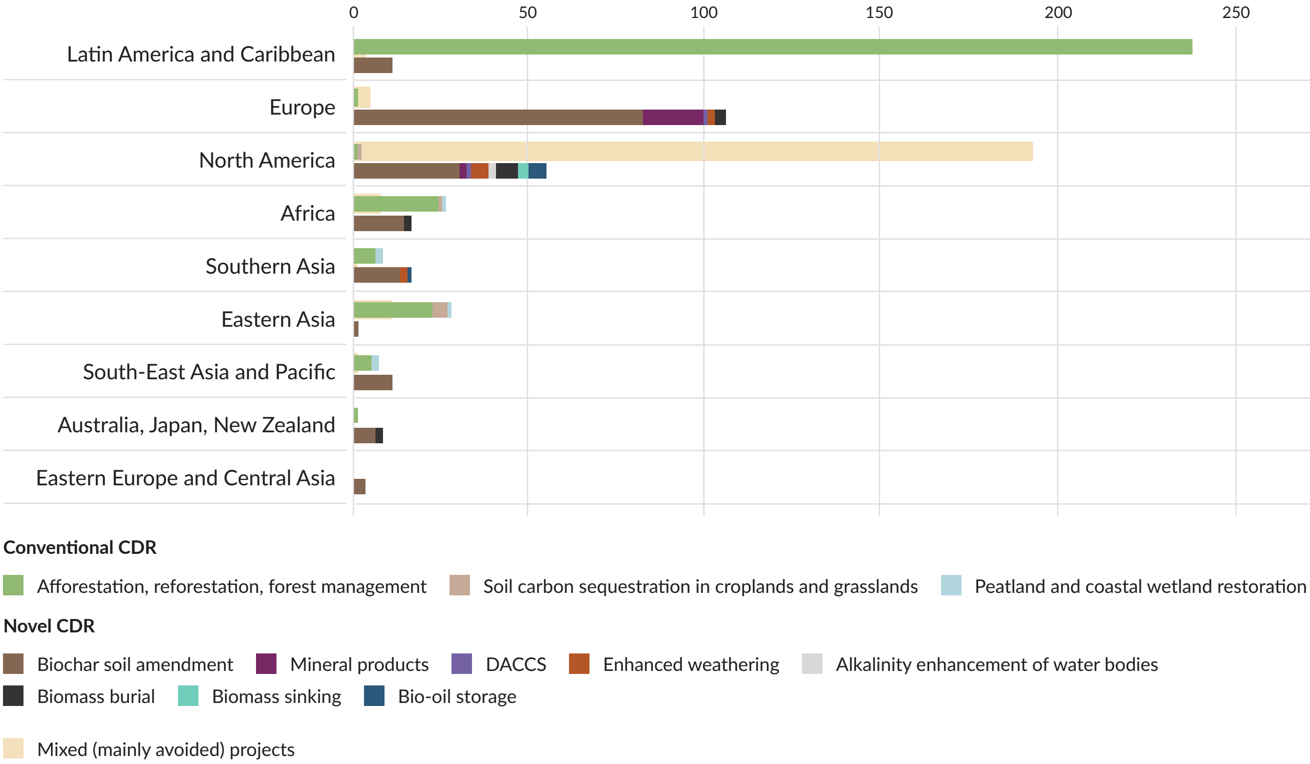
Figure 4.3 shows how active CDR credit projects were distributed across regions and countries from 2024 to 2025, covering both novel and conventional approaches.

The regional distribution (panel a) shows a strong concentration of CDR projects in certain regions. Latin America and the Caribbean stand out with the highest levels of activity, with 74% of contracted conventional CDR and 47% of all active CDR credit projects on the VCM. Europe leads in novel CDR deployment, hosting 48% of all novel projects. Europe is almost entirely focused on novel CDR, with a notable deployment of biochar (86 projects). Africa ranks third with 9.2% of all active VCM projects and a relatively balanced share between conventional and novel CDR, especially driven by afforestation, reforestation and forest management (25 projects) and biochar (18 projects). North America has 8.2% of active CDR projects with a relevant share of biochar (18 projects), and the highest deployment of enhanced weathering (5[ii]) and bio-oil storage (6 projects). Southern Asia and South-East Asia and Pacific also host a notable share of biochar projects (16 and 11 projects, respectively), while Eastern Asia shows relevant deployment in conventional CDR, particularly afforestation, reforestation and forest management (23 projects). In

ii North America would count the highest number of active CDR projects on the VCM in 2024–2025 if we were to include projects with mixed methodologies without a clear removal focus, which applies to all improved forest management projects in North America.

Number of active CDR projects in the VCM, 2024–2025

a) Number of active CDR projects by region



b) Number of active CDR projects by country

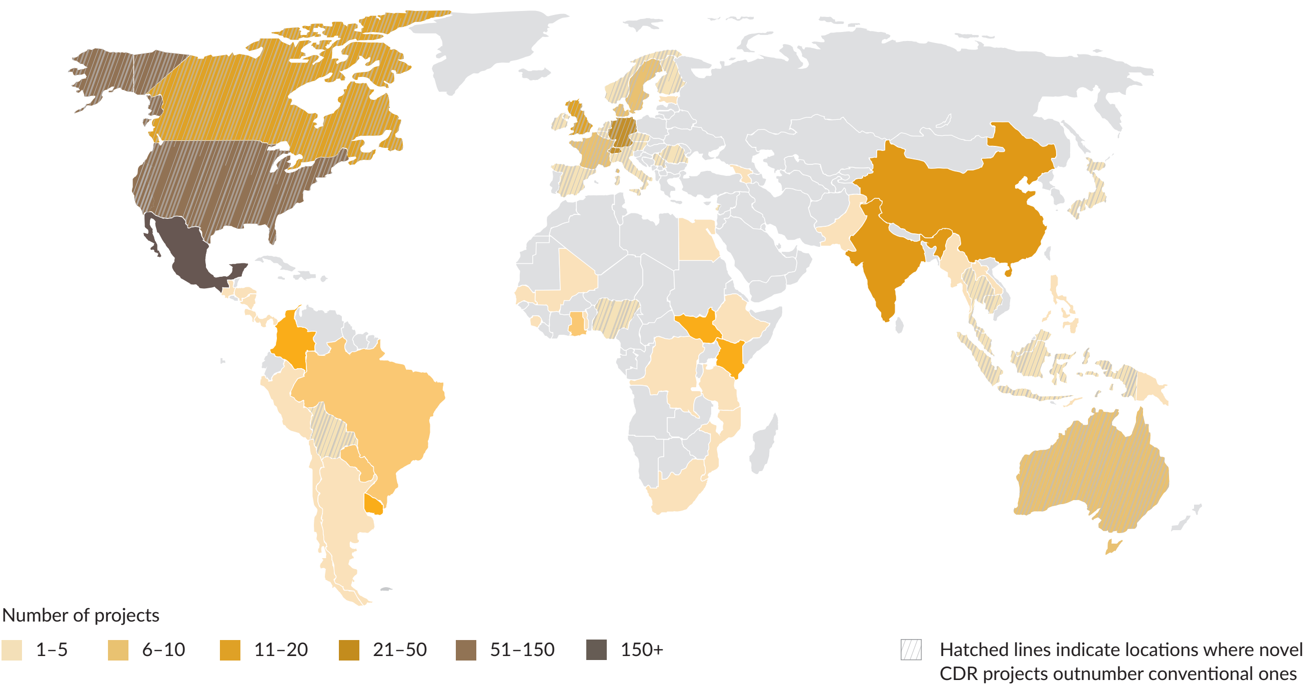


Figure 4.3 *Number of active CDR credit projects in the VCM (a) by region and (b) by country, 2024–2025. Active projects are those that issued or retired credits in at least one of the two years covered (2024–2025); projects with forward contracts but no issued or retired credits are excluded. Section 4.2.1 of the Technical Annex provides a detailed list of how each project class and type is mapped to the corresponding SoCDR method. (Note that regional classifications have been updated since The State of CDR 2nd Edition: Mexico is now categorized within Latin America and the Caribbean rather than North America.)*

other regions, such as Australia, Japan and New Zealand, as well as Eastern Europe and Central Asia, CDR activity remains comparatively limited.

At a country level, Mexico (37%) hosts the largest shares of active CDR credit projects for 2024 to 2025, followed by much smaller project shares in the United States (6.6%), India (6.0%), Germany (5.4%), China (5.4%) and Colombia (4.6%). The country map (Figure 4.3b) further highlights which project class – novel or conventional CDR – is dominant. Novel CDR deployment is most concentrated in the United States (16%) and Germany (14%), while conventional CDR is most dominant in Mexico (59%), followed by China (8.8%) and India (4.1%)

Under Article 6, the distribution of CDR credit projects shifts towards developing countries, with India representing approximately half of conventional and novel CDR credit projects that have undergone prior notification under the PACM.

Pricing

There is considerable variation in CDR credit prices in the VCM, both between and within project classes. While conventional CDR credits tend to trade at relatively low and narrow price ranges, prices for credits from novel CDR methods are generally higher and vary more widely (see Table 4.3).

Average market price (US$) of contracted credits by project type, 2024–2025

Project type	2024	2025
Novel CDR		
Mineral products	700	1,301
DOCCS	1,381	1.100
DACCS	315	593
Alkalinity enhancement of water bodies	451	279
Enhanced weathering	303	407
Bio-oil storage	337	362
BECCS	245	364
Biomass sinking	250	250
Biomass burial	101	127
Biochar soil amendment	132	136
Conventional CDR		
Peatland and coastal wetland restoration	28	29
Afforestation, reforestation, forest management	15	17

Table 4.3 *Note: The price per tonne is not necessarily the same as cost per tonne. Costs may be lower, allowing for a profit margin, or higher, if subsidizing the sales price with external funding. A price premium is already evident for VCM credits that obtain corresponding adjustments via Article 6, but data on this is not yet available for CDR credit projects. Note that the novel CDR price data is based on a small number of public data points.*

CDR purchasers

Based on insights from CDR.fyi and nbs.CDR.fyi, purchasers for both novel and conventional CDR are highly concentrated in the software sector. In novel CDR, 15% of unique purchasers came from the software sector and accounted for 87% of the total tonnes contracted from 2024 to 2025. In conventional CDR, 46% of purchasers came from the software sector and accounted for 80% of total tonnes contracted. Microsoft Corporation is the clear leader in both markets, having contracted 82% of total novel CDR tonnes and 76% of total forward conventional CDR tonnes from 2024 to 2025. An assessment based on the number of unique purchasers reveals that around half of both novel CDR purchasers (49%) and conventional CDR purchasers (55%) have a background in one of three sectors: software, financial or service. Purchasers from the United States dominate both novel (26%) and conventional (37%) CDR. The increase in voluntary advanced market commitments, such as Frontier (a consortium of buyers, who have committed to buying over US$1 billion of novel CDR) the Symbiosis Coalition (who have committed to buying 20 Mt of conventional CDR) have also provided a key conduit for such investments. As a result, there are now more purchasers of forward CDR contracts in novel CDR than in conventional CDR.

4.3 Quality considerations

Several characteristics are considered key to assessing the quality of carbon credits, including additionality, conservative quantification, permanence and the avoidance of double counting. Next to these basic criteria, safeguards against social and environmental harms, appropriate distribution of benefits, and robust governance of the underlying carbon crediting programmes also remain essential. A sizeable literature has documented systemic quality problems across these domains in the most common forms of carbon credits on today's market.[11-14] This triggered a wave of methodological and institutional reforms, extending across the broader carbon crediting landscape. The ecosystem is evolving rapidly, with new standards, methodologies and project types emerging alongside entirely new categories of actors, including carbon credit rating agencies such as BeZero, Sylvera and CalyxGlobal, insurers like Kita and Oka, and buying consortia such as Frontier. Whether or not these developments will fundamentally address the persistent quality issues the market faces remains unclear, including for CDR.

Quality CDR depends not only on the underlying technology but also on the strength of the broader supply chain, methodologies, audits and systems of finance and governance. Conventional CDR credits tend to suffer many of the same challenges that avoidance credits do, but particularly face challenges with the durability of their mitigation outcome. Novel CDR approaches are often structurally designed to address several of the quality challenges carbon credits generally face, for instance by offering greater permanence and more direct MRV protocols. However, independent scientific assessments of their real-world performance remain limited. For novel CDR in particular, challenges include: the provenance of biomass for BECCS and biochar, which must be sourced sustainably to avoid negative impacts on food security and ecosystems; the additionality of projects, since some processes, such as biomass gasification that yields biochar as a by-product, offer limited net benefit; and the permanence of storage, where long-term security and reliable MRV systems are nascent. In addition, significant uncertainties persist around the measurement of geochemical processes such as enhanced weathering and ocean alkalinity enhancement, as well as the lifecycle emissions of energy-intensive approaches such as DACCS.

Looking ahead, several important developments are shaping the landscape on CDR quality. New standards are emerging, with the PACM under Article 6.4 having articulated an ambitious vision for high-integrity carbon removal. However, realizing that vision depends critically on the development of CDR-specific methodologies by the Article 6.4 Supervisory Body and their use in Article 6.2 cooperative approaches which do not have such safeguards.[15] The EU CRCF Regulation also holds potential, though early assessments highlight troubling flaws, even as revisions and updates are underway.[16]

Box 4.2 Limitations and knowledge gaps

- Pricing data on the VCM at large remains opaque, meaning that information is limited on the various factors affecting price formation – including the shares that go to intermediaries.

- As a shift begins from a spot-market focused VCM to an increasing blend of financial mechanisms to cover the growing range of CDR technologies, questions related to assessing financial additionality and the avoidance of double counting between country and corporate ledgers for particular projects will become more vital.

- Manual collection remains necessary for tracking contracted volumes of conventional CDR.

- The exact volume of transitions of CERs from the CDM into new Article 6.4 Emission Reductions under the PACM remains unclear, as does the extent to which Article 6 overall will provide a source of demand for CDR projects.

4.4 Outlook

As we approach the 2030s, the outlook for the voluntary market for CDR is characterized by both challenges and opportunities. In the increasingly interconnected carbon market that has emerged since the Paris Agreement, a key area for attention will be the development and adoption of common standards with wide geographic acceptance. Frameworks such as the Core Carbon Principles under the Integrity Council for the Voluntary Carbon Market (ICVCM) have been viewed as a potential part of this convergence, as has the EU CRCF. The standard set under the PACM of Article 6.4 is also being looked to as one that can guide the development of CDR credit projects and further catalyse voluntary demand. Setting such a framework could drive fungibility of units, promote interlinkages and enable the more rapid scaling of mitigation projects – all of which are needed. However, without careful attention to ensuring the consistent quality of the credits traded across linked platforms, market dynamics could very quickly create a "race to the bottom" where high-quality credits are priced out. The risk of lower-quality credits flooding carbon markets is generally higher for non-CDR forms of mitigation outcomes but remains a general concern across all activity types.[17, 18]

Robust demand in carbon markets is critical for the scaling of CDR. At present, most demand stems from voluntary net-zero commitments. However, the vast majority of novel CDR was contracted by one company (Microsoft), with only a small increase in volume from other buyers, indicating that demand is likely insufficient to meaningfully scale solutions. This is particularly the case as reports in April 2026 indicate that Microsoft could be pausing their purchasing programme.[19] The important role of scaling CDR on the path to net zero was underlined during the revision of the Corporate Net Zero Standard 2.0 of the Science Based Targets initiative (SBTi). To offset the significant volumes of residual emissions that are projected, planning for increased CDR capacity needs to begin now.[1] Some emerging literature argues GHGs emitted should be removed in a like-for-like manner, requiring the durability of the removal to match the permanence of the emission in the atmosphere.[20,21] The increasing integration of more durable forms of CDR into the ETS (see Chapter 5) is a notable but insufficient step in this direction.

There are various challenges for voluntary demand for CDR, which further underscore the importance of fostering robust standards and frameworks. For example, there is the perception that scaling CDR could delay emissions reductions.[22] Additionally, even when investing in durable CDR, the delivery risk is significant. One key industry where these challenges are apparent is aviation. The compliance phase of the CORSIA scheme, which begins in 2027, will prompt airlines to either directly mitigate their emissions below the established 85% of 2019 baseline or offset their ongoing emissions. Given the relative costs involved, many airlines likely will opt to offset their emissions with CORSIA-eligible units. Herein lies a central tension, as the CORSIA criteria – developed prior to the commercial emergence of many forms of durable CDR – have also led to difficulties as a pathway for CDR development, for example, by relying on access to corresponding adjustment via Article 6.2 of the Paris Agreement; this can be a challenge if that CDR unit is not already being counted towards a nation's inventory.[23] As a result, airlines voluntarily purchasing some novel CDR credits remain unable to surrender them for CORSIA compliance. This challenge highlights the frictions that persist in driving a more fungible and higher quality carbon market.

Currently, the VCM plays a critical role in financing CDR. CDR remains a small share of overall market activity by volume but dominates market value and innovation (see Chapter 2). Conventional CDR leads issued and retired volumes, while novel CDR is characterized by high prices, extensive forward contracting and limited near-term delivery. Demand is concentrated among a small number of buyers and sectors, and quality varies across CDR methods and project types. This shows a market that is still forming, one that is capable of early deployment and experimentation but not structured to deliver CDR at the scale required for broader climate goals. Thus, additional measures clearly will be necessary, including policy support (see Chapter 5).

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Chapter 5

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Women from the Gond community in Central India rest in the shade of a mango tree near forest-adjacent paddy fields. By Aaran Patel

Chapter 5 | Policy making and governance

CDR is, above all, a global public good, and the benefit it provides – removing atmospheric CO_2 – means that appropriate policy and governance frameworks are needed to ensure it can be scaled effectively and deployed responsibly.[1,2] While policies supporting conventional CDR have long been a focus, though not necessarily with CDR as the topline objective, policies for novel CDR have increased in recent years, particularly in terms of developing CDR supply. But they remain fragmented, with less focus on creating demand and developing governance frameworks.

Key insights

- Analysis of novel and conventional CDR policies across G20 countries, which together represent three-quarters of global GHG emissions[3] and the majority of countries with novel CDR policy, shows that most novel CDR policy focuses on building CDR capacity through supply-side support, with less attention so far on creating demand and ensuring robust governance. Conventional CDR policy is both more prevalent and more developed across countries, focusing on afforestation and reforestation.

- The most significant recent policy shift has been in the United States, which had been a leader in CDR policy, but under the Trump administration has frozen or dismantled funding and support for climate action, including CDR. Policy dismantling and uncertainty pose a broader risk to CDR momentum: while progress in other geographies may partly offset reversals, there remains a risk that the overall pace of CDR development will slow, particularly if net-zero targets are weakened or deprioritized. Aside from the United States, policy for novel CDR is progressing in other countries including Canada, Germany and the United Kingdom, but remains in development.

- On the demand side, while purchases of novel CDR on the voluntary carbon market have been the primary driver of growth, interest in adding carbon removals into compliance regimes is growing. The European Union, United Kingdom and Switzerland are actively exploring frameworks that could enable the future use of novel CDR in regulatory schemes.

- Governance frameworks for novel CDR remain largely underdeveloped, with some exceptions, such as the CRCF.

- More than 100 countries have set net-zero targets,[4] implying a role for CDR (and a need for policy to follow). However, only around one-third of countries mention novel CDR in their long-term strategies (LTSs) and few mention it in their NDCs.[5] In both, greater specificity would improve the transparency and comparability of national CDR commitments. Ultimately, translating targets into policy will depend on domestic political processes; among the G20, only the EU's land sector net removal target is legally binding.

- Tracking the sequence and focus of CDR policy, including the evolution of targets into policy, can provide blueprints for other countries taking initial steps to advance CDR and an understanding of where commitment is leading to action.

Because CDR is a public good, policy plays an outsized role in supporting its development and deployment.[6] CDR generally lacks a natural market – unlike other climate change mitigation technologies like solar photovoltaics or electric vehicles that provide essential services (i.e. electricity and transport) and are entering incumbent markets. As such, policy intervention — whether through legislation, regulation or other mechanisms — will be needed to create both supply and demand for CDR.

Robust governance frameworks are also critical to ensuring that CDR is scaled responsibly. Responsible scaling is defined in different ways but often includes: establishing safeguards to ensure that CDR approaches and technologies are not inhibiting emissions reductions;[7] minimizing negative impacts on the environment;[8] using robust and consistent MRV protocols regarding quantities of CO_2 removed;[9] and engaging with local communities.

This chapter assesses the current state of policy and governance for CDR at the national level; the regional level, in the case of the European Union; and the international level.[i] National and EU CDR policies assessed in this chapter are included in the data portal for *The State of CDR 3rd Edition*, and each is tagged based on the policy typology described below.

Our analysis of CDR policy focuses on G20 countries and uses a suite of policy databases. For novel CDR, we use: IEA's Policies and Measures Database; Climate Change Laws of the World; Carbon Gap's EU & International Carbon Removal Policy Database; and Carbon Removal Standard Initiative's Carbon Removal Quantification, Integration and Policy Database. We supplement these with country-specific databases and research. For conventional CDR, we rely on the Food and Agriculture Policy Decision Analysis Tool from the Food and Agriculture Organization of the United Nations (FAO) and the Policy Inventory for Mitigation Actions in the Agriculture, Forestry and Other Land Use Sectors (PIMA-AFOLU) database of the Organisation for Economic Co-operation and

[i] While subnational policies may also be important for advancing CDR, we do not cover them in this chapter.

Development (OECD); the latter provides the most comprehensive overview of mitigation-specific policies in the AFOLU sector in OECD and G20 countries and has been verified by country experts. Covering more than three-quarters of 2023 global GHG emissions[3] and most novel CDR policy, the G20 countries are a manageable and representative subset of global developments in CDR policy.

Additionally, because the countries (plus the European Union[ii] as a supranational organization) that make up the G20 closely match the list of largest historical GHG emitters, they are important to track, as they arguably have a distinct responsibility to develop the technologies that can help address their historical emissions.[10]

5.1 Status of CDR policy

Policy and governance for CDR is advancing but remains fragmented across countries. Only a few jurisdictions have taken far-reaching steps, such as the binding quantitative land sector net removal target in the European Union, emerging quantitative CDR ambitions in national strategies, and targeted [iii]-creation instruments such as tax credits and purchase schemes for novel CDR in the United States. Overall, CDR-relevant measures remain scattered and often underdeveloped, suggesting that it is not yet seriously treated as a public good and an integral component of climate policy. In the following section, we set out a typology of CDR policy and assess policy focus and sophistication for both novel and conventional CDR across G20 countries.

Types of CDR policy

Recent years have seen an expansion in systematic tracking of climate policy via databases including the Climate Policy Database,[11] Climate Change Laws of the World[12] and the IEA Policies and Measures Database.[13] These efforts enable assessment of which governments are acting to address climate change and which instruments they deploy.[14] While CDR, as a component of climate policy, lacks a dedicated global policy tracker, initiatives such as Carbon Gap's EU & International Carbon Removal Policy Database[15] and taxonomies tailored to CDR policies are advancing.[16,17]

A central challenge in developing a taxonomy for CDR policy is including broad enabling measures that are relevant to CDR alongside CDR-specific instruments – especially across sectors where energy, land and ocean regulations intersect. Additionally, legislative frameworks in many countries are evolving rapidly, creating a dynamic regulatory landscape. For example, Germany's High Seas Dumping Act (*Hohe-See-Einbringungsgesetz*)

[ii] The African Union is also a member of the G20, but we did not assess it here because it does not set legally binding climate policy for its member countries as the European Union does.
[iii] The CDR purchase pilot prize has stalled under the current Trump administration, but there is Congressional direction in FY26 appropriations to continue it.

previously permitted the introduction of substances into the marine environment only under narrowly defined research exemptions. As a result, certain ocean-based CDR activities were effectively constrained until the law was amended in 2026 to allow commercial storage of CO_2 in the seabed. Because the Act is not framed as climate legislation, it is typically excluded from standard climate policy databases, despite its relevance for CDR deployment.

Similarly, measures that are not framed as climate policy may be critical enablers of CDR activities. Indirect policies – those that do not target removals explicitly but create foundational conditions for CDR or indirectly incentivize supply or demand – are, therefore, relevant for CDR policy analysis. They vary widely in design across countries, complicating comparative assessment and progress tracking. This includes interventions in the agriculture sector and the LULUCF sector that result in durable carbon storage.[18] Furthermore, some conventional CDR-related policies have existed for decades and have gradually been repurposed towards a carbon focus; for instance, Canada's natural resource framework now explicitly emphasizes ecosystem-based forest management with carbon sequestration as one objective.[19] Policies that broadly promote land-based mitigation measures[20] such as afforestation, reforestation and soil carbon enhancement. These approaches, often labeled as nature-based solutions, require careful disaggregation to distinguish between those elements that are genuinely CDR-relevant and those aimed primarily at reducing emissions.

Another challenge is separating policies focused on CDR from those supporting point-source fossil carbon capture and use or storage (CCU/CCS), which can result in reduced emissions – not atmospheric removal. In the United States, for instance, many activities fall under the term "carbon management", which encompasses both CDR, CCU and CCS.[21] Additionally, numerous jurisdictions are advancing regulations for geological carbon storage and/or CO_2 transport primarily with fossil CCU or CCS in mind; nevertheless, these frameworks can also enable deployment of some types of novel CDR. Owing to the definitional challenges and extensive interlinkages with adjacent sectors, a comprehensive, global inventory of CDR-relevant policies is lacking.

CDR policy analysis

In this chapter we develop a FOAK database of CDR-relevant policies across G20 countries and the European Union. This database captures some core elements of CDR policy action and enables a broader understanding of emerging governance trends.

We define a CDR policy as one that covers any single public measure – such as a law, regulation, strategy, target or official communication – that is in force, enacted or formally announced. Policies may span multiple instrument types and sectors and are included when they have a clear, demonstrable connection to the CDR methods considered in this report, including enabling or constraining relevant land- or ocean-based activities.

Building on existing literature on CDR governance, we organize these policies into three categories – foundational, supply-side and demand-side – spanning both conventional and novel CDR (see Table 5.1). Foundational measures create or remove legal barriers for CDR and address externalities, thereby enabling CDR and further policies. These include binding and non-binding economy-wide GHG targets and frameworks, MRV systems, environmental safeguards and community engagement provisions. Supply-side instruments lower the cost, risk or uncertainty of delivering verified removals through public funding, tax incentives, infrastructure support and early-stage funding for RD&D. Demand-side instruments create or expand markets for verified removals via method-specific targets and obligations, public procurement and integration into carbon markets, including ETSs. This demand/supply framing is consistent with earlier policy analyses[22,23] and is especially salient for CDR because there is little demand without clear incentives. It is, therefore, crucial to examine which strategies and instruments countries use to generate robust and ongoing demand signals for CDR.

Understanding the sequencing of policies in terms of focus area, instrument type and stringency can also provide insight on what is most effective under different circumstances. Within the typology assessed here, foundational policies can form the baseline that supply-side policies can refer to, while demand-side policies subsequently expand the market for CDR purchases. Such a sequencing can be observed in the European Union,[24] while others have favoured initiating CDR policymaking with supply-side measures and instituting foundational policies later.

Typology for CDR policy assessment

Policy category	Policy objective	Examples
Foundational	Introduce or remove legal barriers for CDR, laying the groundwork for CDR development and deployment	Framework documents that set strategic direction for climate policy or economywide targets MRV policies Policies for environmental safeguards Policies for community protection
Supply-side	Reduce cost, risk or uncertainty of supplying CDR	Funding for RD&D Tax incentives Contracts for difference Funding for CO_2 transport and storage infrastructure
Demand-side	Create or expand markets or other incentives for buyers to purchase CDR	CDR method or sector-specific targets Integration of CDR into compliance markets Tax incentives for buyers Government procurement of CDR (e.g. through reverse auction)

Table 5.1

CDR policies around the world

Previous analyses indicate that CDR policy is still relatively sparse across developed and emerging economies[16,17] and across the geographies considered in earlier editions of *The State of CDR* (i.e. Brazil, Canada, China, the European Union, Japan, Saudi Arabia, the United Kingdom and the United States). Across the G20 and other countries considered in this report, several have adopted binding, economy-wide, net-zero targets including Australia, Canada, the European Union, Japan, Republic of Korea, the Russian Federation and the United Kingdom (see Section 5.2). However, only the European Union – and, by extension, all 27 EU Member States – has adopted a binding, quantitative land sector target in law.[iv] It requires 310 $MtCO_2e$ of annual net removal by 2030, corresponding to an increase of the land carbon sink by 42 $MtCO_2e$ compared with average levels from 2016 to 2018. This comparison is particularly important because estimates of the land carbon sink can change as forest and land-use data are updated over time. However, this conventional net removal target may not be reached, with the European Environment Agency concluding that it is highly unlikely to be realized by 2030 and research indicating that the forest sink is declining.[25,26] As of the end of 2025, no G20 country has an explicit, legally binding, CDR-specific quantitative target, though several emerging frameworks, strategy documents and long-term plans signal growing interest in removals and set non-binding goals, including sectoral or method-specific targets.[v]

Compliance carbon markets can represent a powerful demand signal for CDR, though the strength of this signal depends critically on the type of market and the role assigned

[iv] LULUCF Regulation (Regulation (EU) 2018/841, amended 2023)
[v] Mitigation targets, including net-zero targets, are often designed as net targets that rely on CDR in one way or another.

to removal units within it. Carbon market arrangements that involve CDR can be differentiated according to both the type of units traded and the level of compliance obligations attached to them.[27] At one end are full compliance systems, such as ETSs, where removals are integrated directly into the main carbon market. In these systems, certified removals can function analogously to emissions allowances, serving as the strongest instrument for creating demand for CDR. In the middle are quasi-compliance systems, where regulators allow a limited share of obligations to be met with CDR credits from government-led or UN-administered crediting programmes. At the other end are voluntary mechanisms (see Chapter 4), generally operated by private organizations, which issue CDR credits but do not yet create legally binding demand – though they may be linked to regulated markets.[28]

Only a small subset of ETSs currently creates explicit compliance demand for CDR.[29,30] Among existing ETSs, New Zealand remains the clearest example of structural integration. Forest-based removals are fully embedded in the main allowance market and can be used for compliance.[29–31] Recent announcements signal the government's intention to amend legislation so that "non-forestry removals" could be recognized as ETS activities and an Assessment Framework for Carbon Removals has been published. However, methodologies for non-forestry removals remain to be developed, and the timing of legislative enactment is uncertain.[32] Similarly, Australia's reformed Safeguard Mechanism allows Australian Carbon Credit Units (ACCUs) generated through voluntary abatement activities under the ACCU Scheme, including from conventional CDR projects, to be used for compliance. Additionally, Japan considered novel CDR in the voluntary phase of GX-ETS. The compliance phase, which began in April 2026, accepts limited types of carbon credits, and discussion is ongoing as to how to incorporate novel CDR.[33,34]

Important developments are taking place in European compliance markets. In the United Kingdom, the UK ETS Authority has committed to integrating novel CDR into the UK ETS. Following a multi-year consultation process culminating in the government's July 2025 response, the United Kingdom intends to incorporate removals such as BECCS and DACCS into the scheme, with legislation in 2028 aiming for implementation in 2029. The proposed design includes a dedicated treatment for removal units within the UK ETS, with further technical details subject to additional consultation.[35] In the European Union, the 2023 EU ETS Directive requires the European Commission to assess by July 2026 how CDR could be integrated into the EU ETS, potentially opening another major compliance market to removals in the medium term.

A larger set of compliance markets creates demand through more limited, credit-based approaches. A 2025 International Carbon Action Partnership thematic brief on CDR inclusion in selected ETSs finds that several compliance systems — including those in Australia, Canada, China and the Republic of Korea — allow conventional CDR units, mainly from forestry, to be surrendered for compliance obligations.[36] In most of these systems, eligible units are generated via domestic crediting mechanisms operating in parallel to the main compliance market, with quantitative limits applied in several (though not all) cases.[31,34] China's national ETS allows covered entities to use domestic China Certified Emission Reduction (CCER) offsets for up to 5% of their verified emissions, and the relaunched CCER framework includes afforestation and mangrove restoration methodologies.[31,34] The Republic of Korea's ETS similarly permits a capped share of up to 5% of compliance requirements to be met with credits from conventional CDR, including forest and certain ocean-based projects.[31]

Other emerging systems are adopting similar structures. Brazil's 2024 Sistema Brasileiro de Comércio de Emissões de Gases de Efeito Estufa defines Certificates of Verified Emission Reduction or Removal as eligible compliance assets from the outset, with specific limits and methodologies to be set through secondary regulation.[31]

We assess existing policies through a qualitative, expert-based review of each country's regulatory framework, instruments and implementation status across both conventional and novel CO_2 removal groups (see Table 5.2). The assessment considers the presence and strength of supply-side support and demand-side mechanisms (such as quantitative targets, public procurement and the type of integration into compliance markets) and whether those are binding. Based on this, countries are classified into four levels of policy development.

1. Emerging: where initial frameworks exist;
2. In active development: where a broader mix of instruments and non-binding demand signals is in place;
3. Advanced: where strong, often binding demand-side measures exist; and
4. Not evident: where no meaningful policy signal can be identified.

Across the considered entities, most policy activity is still concentrated on conventional CDR, primarily by repurposing and strengthening land-use, forestry, agriculture and ecosystem restoration policies to function explicitly as carbon sinks. A smaller group of countries places stronger emphasis on novel CDR. The United States and the United Kingdom, for example, focus on DACCS and BECCS; Brazil stands out for its pioneering enhanced weathering framework; and the European Union provides more support for biochar than other regions. In many other jurisdictions, policy for novel CDR remains limited and largely indirect, emerging mainly through CCU/S-oriented regulations and infrastructure that can support both point-source capture and future deployment of novel removal methods.

Overview of conventional and novel CDR policy development across G20 countries and regions

Country/ Region	Conventional CDR	Novel CDR	Major foundational, supply and demand policies
European Union	✓✓✓	✓✓	Binding LULUCF net removal target for 2030; regulatory framework for CO_2 storage and CDR certification.
United Kingdom	✓✓+	✓✓+	Planned integration of novel removals into emissions trading; conventional removals under review; legislative foundation (Energy Act, 2023) and RD&D for BECCS and DACCS; GHG Removals Business Model; contracts for differences framework; and non-binding quantified CDR ambition.
Canada	✓✓+	✓✓+	Robust carbon-pricing and offset systems that credit land-based removals (DACCS protocol under development; BECCS protocol development to begin in 2026),[37] combined with substantial grants, tax credits and early procurement to support novel CDR projects.
United States	✓+	✓✓	Conventional CDR supported through broad land policies, but without dedicated or binding targets. Novel CDR was driven by federal funding, but much of this is now uncertain. One key policy support, the 45Q tax credit, remains and supports deployment of some types of novel removal.
Brazil	✓✓+	✓+	Extensive regulation and incentive schemes for conventional CDR; pioneering policy framework for enhanced weathering (Remineralizer Law and National Fertilizer Plan); new ETS to create space for removal certificates.
India	✓✓+	✓+	National non-binding land-use sink target and extensive regulations; enabling regulation for BECCS and DACCS.
Germany	✓✓	✓✓	Regulation and incentive schemes for conventional CDR; existing CCU/S policy and pilot projects; novel CDR in exploratory/early phase; budget for government procurement of CDR.
Japan	✓✓	✓+	Regulation and incentive schemes for conventional CDR; growing RD&D, pilot funding and J-Credit scheme coverage for novel methods, with integration of some types of removal into the GX-ETS.
Australia	✓✓+	✓	National carbon crediting for land-based removals via the ACCU Scheme and extensive land policies; novel removals are still at an early, mainly supply-side development stage.
Saudi Arabia	✓+	✓+	National plans for expanding land-use sinks; GHG Crediting and Offsetting Mechanism that creates early market space for future CDR and novel removals.
China	✓✓	✓	Regulation and incentive schemes for conventional CDR; novel CDR in exploratory/early phase mainly through CCUS projects.
France	✓✓	✓	Regulation and incentive schemes for conventional CDR; existing CCU/S policy and pilot projects; novel CDR in exploratory/early phase.
Indonesia	✓✓+	+	National non-binding land-use sink target and extensive regulations; emerging regulation of novel removals through geological storage.
Italy	✓✓	+	Regulation and incentive schemes for conventional CDR; novel CDR activity remains limited, with national efforts focused mainly on the regulation of CO_2 storage and transport rather than dedicated removal support.
Republic of Korea	✓✓+	–	Extensive forest and land-use sink programmes and inclusion of conventional removal credits in the national ETS; no identifiable novel removal policies.
South Africa	✓✓	–	Programmes supporting land-use sinks and non-binding targets (NDC 2021); no identifiable novel removal policies.
Türkiye	✓✓	–	Programmes supporting land-use sinks and highlighting the role of conventional CDR in NDC; no identifiable novel removal policies.

Country/ Region	Conventional CDR	Novel CDR	Major foundational, supply and demand policies
Mexico	✓✓	–	Programmes supporting land-use sinks and a non-binding target (NDC 2025); no identifiable novel removal policies.
Argentina	✓✓	–	Land-use sink policies backed by instruments such as the Argentine Carbon Fund, which procures afforestation/ reforestation credits; no identifiable novel removal policies.
Russian Federation	✓✓	–	Land-use sinks included in domestic crediting; no identifiable novel removal policies.

Table 5.2 *Notes: Countries are classified along four levels of policy development:* ✓ *= Emerging,* ✓✓ *= In active development,* ✓✓✓ *= Advanced,* – *= Not evident/ no policy signal, and* + *= halfway between categories. Elements mentioned in the table are not exhaustive of all CDR policy in the jurisdiction. Based on an analysis of sources including IEA, 2025[13]; OECD, 2025[18]; CRSI, 2025[38]; FAO, 2025[39].*

International CDR policy and governance

International policy and governance can complement national CDR policy, enabling cooperation and accelerating action by:

- Facilitating cooperation across countries, sharing lessons learned, improving the efficiency of technology and policy development, and avoiding duplication of effort;
- Establishing common rules and approaches to manage cross-boundary risks, trade-offs and negative impacts of CDR approaches;
- Addressing questions of international equity around distribution of effort; and
- Establishing mechanisms for public participation.[40]

CDR policy remains in early, fragmented stages of development across regions and countries, so international coordination is needed to help chart a coordinated path forward (see Box 5.1), particularly because the benefit of CDR is global, but any ancillary impacts are likely to be local.

Box 5.1: State of international CDR governance and institutions

In other areas of energy and climate policy, international governance has helped to coordinate global actions, accelerate innovation and deployment, and set standards; however, international governance for CDR remains fragmented due in part to the relative nascency of CDR policy and technology. Greater near-term international coordination is urgently needed to scale up CDR because of the decades-long process of developing novel technologies and the diversity of actors involved in their adoption.[40] In the absence of more comprehensive governance, a patchwork of individual state and non-state actors risks sluggish deployment, misaligned incentives, uncoordinated national efforts and inconsistent and divergent standards.

A recent assessment of CDR initiatives (published in our first Discussion Paper) with clear plans or mandates related to governance activities reveals a dearth of international governance capacity for CDR, particularly around rules, standards and mechanisms for transparency. Across 12 assessed CDR initiatives, governance functions related to signaling, multilateral coordination and data/learning were most prevalent. By contrast, functions related to implementation, finance and capacity building, as well as policy analysis, were less common across the sample. Notably, few initiatives included focused on strengthening rules, standards and mechanisms for transparency. For instance, among more advanced initiatives, a category that includes the Group of Negative Emitters and Mission Innovation's CDR Mission, all were found to contribute meaningfully towards signaling and multilateral coordination; none, however, exhibited robust governance related to standards, rules and mechanisms for transparency and accountability – at least not yet. Given the need for convergence on MRV protocols, this role may be most effectively fulfilled by a small number of coordinated entities rather than a proliferation of institutions (i.e. the need is not necessarily for more institutions but for more coordinated, international efforts to harmonize methodologies and policies). These results not only identify gaps but underscore the importance of new and existing international efforts to address them. Moreover, overlapping efforts suggest a need for enhanced coordination to reduce duplication of effort and optimize resources.

Filling gaps will likely require expanded activities at existing organizations as well as the formation of new institutions. Historical evidence shows that nascent organizations with a limited set of functions can evolve into durable institutions that grow in scope to serve a broader set of activities over time. Evidence also demonstrates that trusted information can play an important role in building legitimacy, especially when coupled with early efforts to enhance awareness of the potential gains of cooperation. Hence, the challenge the field faces today is how to fill the governance gaps with adaptive, nimble and robust institutions that can evolve faster than analogous institutions in the past. Countries championing CDR policies and initiatives, such as those described in this chapter, can play a key role in filling gaps through domestic and international initiatives.

The Paris Agreement implicitly relies on CDR and provides legal and procedural context relevant to CDR. Article 4 establishes the balance of emissions and removals in the second half of the 21st century, tacitly acknowledging a role for CDR.[41] Article 5 encourages results-based financial support for carbon and GHG sinks, while Articles 9 and 10 address finance and technology transfer – both essential to scaling CDR capacity.

Article 6 of the Paris Agreement offers the clearest international cooperation channel[27]: Article 6.2 enables bilateral transfers of Internationally Transferred Mitigation Outcomes, first used for a durable-CDR transfer between Norway and Switzerland in 2025; Article 6.4 creates a UN-supervised crediting mechanism under a Supervisory Body that could cover both conventional and novel CDR. Progress has been made on methodologies, removals and reversal-risk management. At the same time, comprehensive, operational MRV for CDR under Article 6.4 remains incomplete, posing challenges for integrity and investment decisions. REDD+ has been aligned with Article 6.4, but inconsistencies remain.[42] The overall share of removals in the pipeline remains modest (see Chapter 4).

Outside of the Paris Agreement, other international frameworks, such as the Convention on Biological Diversity, are relevant to certain types of CDR. Particularly for marine CDR in waters outside of national jurisdictions, international regimes – including the London Convention and Protocol and the High Seas Treaty– are relevant but do not provide a comprehensive governance regime.[43] Across both conventional and novel CDR, foundational principles in customary international environmental law apply, such as the precautionary principle, prevention of transboundary harm and due diligence. These principles underpin environmental assessment and risk management and can act as limiting conditions for developing and deploying CDR approaches with uncertain ecological or social impacts.

Government-led multilateral initiatives are beginning to coordinate research, early deployment and longer-term planning for CDR, but they focus less on binding, comprehensive governance. The Mission Innovation CDR Initiative – co-led by the United States, Saudi Arabia and Canada with participation from Australia, China, Japan, the Netherlands, Norway and others – structures R&D across three CDR methods. The initiative supports early deployment via the CDR Launchpad and focuses on novel CDR. In parallel, the Group of Negative Emitters – led by Denmark and including Ethiopia, Finland, Kenya, the Netherlands, Panama, Suriname and Sweden – encourages national planning for net-negative trajectories that include both conventional and novel CDR.

For conventional CDR, ecosystem restoration efforts – such as the Bonn Challenge and regional pledges like Initiative 20x20, AFR100 and ECCA30 – aim to restore hundreds of millions of hectares of degraded land, though reporting often emphasizes pledges rather than verified outcomes. The Glasgow Leaders' Declaration on Forests and Land Use similarly commits to halting and reversing forest loss by 2030 but lacks enforceable sub-targets and transparent monitoring.

5.2 Targets inform policy

Target setting is an important tool for policymakers to signal priorities and allows civil society and the public to track progress and hold governments accountable. Setting targets for CDR, both novel and conventional, can act as a strong demand signal and allow the tracking of progress and the identification of policy gaps. However, countries' climate plans often lack transparency on the extent to which they will use CDR.

Under the UNFCCC, parties can communicate their intended use of CDR in official documents. Parties are required to submit NDCs with mitigation targets in five-year cycles. Previous NDC submissions included targets for 2030. The most recent submissions were due in 2025 and include targets for 2035. Parties are also encouraged to submit long-term strategies that outline their climate goals and plans for 2050 or later. Further, parties were required to submit Biennial Transparency Reports (BTRs) for the first time in 2024, describing in more detail how they plan to meet these targets. While these documents are intended to signal governments' ambitions and plans, they are not always aligned with national policies and actions.

In these submissions, parties rarely provide explicit information on the contribution of removals; however, many indicate the expected contribution of the LULUCF sector to their overall mitigation targets. This is important because most current conventional CDR takes place in this sector in the form of afforestation, reforestation and forest management. Separating out LULUCF removals would help to demarcate them from intentions to reduce emissions resulting from deforestation.

For novel CDR, less information tends to be available on near-term deployment than long-term. NDCs tend not to mention novel CDR methods, which are largely at an early stage of development, while long-term strategies will more often consider these methods. Out of 79 parties that submitted long-term strategies, 20 indicated that they intend to use novel CDR and seven indicated they are considering such use.[5]

In our assessment of NDC and BTR submissions by members of the G20, we found that few provide enough information to judge the contribution of CDR in meeting their targets (see Table 5.3). As of March 2026, 15 members of the G20 have submitted new NDCs with 2035 mitigation targets. Only ten members have provided enough information on the expected contribution of the LULUCF sector to allow an estimation of intended conventional CDR for 2030, 2035 or both. Only the United Kingdom and Australia have provided information on how novel CDR may be used to meet their NDC targets.

Current and proposed CDR for the G20 and other key CDR countries ($MtCO_2$ per year)

Party	Submitted 2035 NDC?	Current LULUCF CO_2 **emissions** (e.g. from deforestation)	Current LULUCF CO_2 **removals** (e.g. from afforestation)	Pledged **change in LULUCF CO_2 removals** by 2030 [and 2035]	Pledged **change in novel CDR** by 2030 [and 2035]
Argentina	N	54	-13	-	-
Australia	Y	29	-103	-19 to -20 [-24 to -27]	-2 to -26 [-3 to -10]
Brazil	Y	886	-383	-125 [-148]	-
Canada	Y	55	-28	-	-
China	Y	5	-1263	-	-
European Union	Y	125	-390	-53	-
India	N*	14	-423	+16 to -4 [-1 to -18]	-
Indonesia	Y	1,157	-483	-12 to -74 [-52 to -100]	-
Japan	Y	9	-69	+29	-
Mexico	Y	18	-216	+16	-
Republic of Korea	Y	4	-47	+15 [+3 to +4]	-
Russian Federation	Y	38	-1,133	-	-
Saudi Arabia	Y	0	-9	-	-
South Africa	Y	35	-69	-	-
Türkiye	Y	3	-70	+12	-
United Kingdom	Y	15	-21	0 [0]	-3 to -5 [-13 to -23]
United States	Y**	176	-1,131	-	-
Democratic Republic of the Congo	N	573	-518	-	-
Ethiopia	Y	196	-79	-44 to -93 [-51 to -106]	-
Thailand	Y	9	-100	- [-25]	-
Switzerland	Y	1	-3	-	-
Nigeria	Y	319	-4	+1 to -10 [+1 to -10]	-

Table 5.3 *Notes: Documents submitted to the UNFCCC by March 2026 were assessed. Current LULUCF emissions and removals refer to the 2014–2023 decadal average, noting national reporting is not always complete and some reported net emissions or net removals are not possible to disaggregate. Pledged changes by 2030 and 2035 are measured against this baseline. France, Germany and Italy are members of the G20 but are represented by the European Union's NDC submission and are, therefore, excluded. We also excluded the African Union, which does not submit a pledge for its members, and included several non-G20 countries that are key in terms of CDR. Green cells indicate an increase in removals, while orange flags a decrease in removals.*

** We assess India's announced 2035 NDC target; however, the country has not officially submitted a new NDC to the UNFCCC as of March 2026.*

***The United States has fulfilled criteria related to its BTR released in 2024 but officially exited the Paris Agreement in January 2026.*

Sources: Dabbs, B., Marshall, C. & Hiar C., 2025[44]; US House of Representatives, 2024[45]

While many countries lack short-term pledges on removals, many more have committed to reaching net zero, implying a role for CDR in meeting their long-term climate goals. As of March 2026, 108 countries have set net-zero targets.[5] In addition to improving the transparency of these pledges, policymakers can take additional actions to make these pledges more credible, including:

- Establishing net-zero targets in law;
- Implementing CDR policies and measures; and
- Comprehensively planning for scaling CDR.

The assessment in Table 5.4 expands on our Insight Report,[46] published in November 2025, in which we assessed the credibility of the G20's CDR pledges against these criteria.

By signing net-zero targets into law, members indicate CDR will be needed to meet climate goals. Further, legally binding targets are more difficult to ignore or reverse and expose future administrations to legal challenges. As of March 2026, 15 members of the G20 have net-zero targets, seven of which have been signed into law.

The adoption of CDR policies is an important indicator that governments are working to achieve their pledges by creating enabling conditions to scale removals (see Section 5.1). While every member describes conventional CDR policies in their BTR (with the exception of India, which has not yet submitted one as of March 2026), far fewer describe policies targeting novel CDR. The United States has a BTR that includes policies for both novel and conventional CDR; however, the document was submitted under the Biden administration, which ended in January 2025, and does not account for the policy shifts undertaken by the current Trump administration (see Section 5.3).

Finally, by integrating CDR and net zero into their national planning efforts, governments show they are working to deliver on their pledges. Parties are required to provide projections both for total net emissions and those at the sector level, with flexibility given to developing countries to meet this obligation. Projections for the LULUCF sector should reflect "existing" or "additional" measures and can indicate whether parties are currently on track to meet their pledges. Similarly, governments can publish analyses on emissions pathways and sector-specific actions to achieve their net-zero targets.

Credibility assessment of the G20 countries

G20 member	Transparency	Legal status	Current implementation		Comprehensive planning	
	NDC provides sufficient information on CDR?	**Net-zero target** in law?	**BTR** describes conventional CDR measures?	**BTR** describes novel CDR measures?	**BTR** has LULUCF projections?	Published plan to reach **net-zero target**?
European Union	✔	✔	✔	✔	✔	✔
Republic of Korea	✔	✔	✔	✔	✔	❍
United Kingdom	✔	✔	✔	✔	✔	✔
Japan	✔	✔	✔	✘	❍	❍
Türkiye	✔	✔	✔	✘	❍	❍
Indonesia	✔	❍	✔	✘	❍	✘
China	✘	❍	✔	✘	✘	❍
India	✔	❍	✘	✘	✘	✘
Australia	✔	✔	✔	✔	✔	✔
Canada	✘	✔	✔	✔	❍	❍
Russian Federation	✘	✔	✔	✘	❍	❍
Saudi Arabia	✘	❍	✔	✔	✘	✘
South Africa	✘	❍	✔	✘	✔	✘
Argentina	✘	❍	✔	✘	✘	✘
Brazil	✔	❍	✔	✘	✘	✘
Mexico	✔	❍	✔	✘	✘	-
United States*		✘	✔	✔	✔	-

Table 5.4 *Notes: A check indicates that the criteria is fulfilled, a circle indicates that the criteria is partially fulfilled, and a cross indicates that the criteria is not fulfilled (see the Technical Annex for more detail). The transparency criteria refers to whether an estimate can be made in Table 5.3.*

**The United States has fulfilled criteria related to its BTR released in 2024 but exited the Paris Agreement in 2026.*

Sources: UNFCCC, 2026[45]; Climate Analytics & NewClimate Institute, 2026 [47]

5.3 Policy deep dives by country

Countries are pursuing different approaches to CDR policy in terms of focus and sequencing as well as the level of policy and governance sophistication. The last two editions of this report included deep dives on Brazil, Canada, China, the European Union, Japan, Saudi Arabia, the United Kingdom and the United States. Here, we consider policy direction and evolution in the United States, Switzerland and Germany, each of which provide compelling examples of different policy directions and approaches. The United States presents a striking example of a country that held a leadership position on CDR policy but is currently backpedalling. Switzerland, which is in neither the European Union nor the G20 and so is not discussed elsewhere in this report, has taken innovative and experimental policy steps on CDR and is home to several leading CDR companies. Germany, the largest EU Member State, is currently shifting from reluctant acceptance of CDR to a more proactive approach.

United States

The United States has been a leader on CDR policy,[48] enacting a range of supportive policies, mainly between 2020 and 2024, under the Biden administration. More than US$8.5 billion was provided in the 2021 Bipartisan Infrastructure Law for demonstration projects and enabling infrastructure, while the 2022 Inflation Reduction Act increased deployment support for each US ton of CO_2 removed with DACCS and BECCS. In addition to these supply-side measures, initial steps to increase demand came with the CDR Purchase Pilot Prize, which was also designed to help set the bar for robust MRV protocols.

However, the current U.S. administration under Donald Trump, who came into office in January 2025, has disrupted funding and support for CDR and cut personnel at relevant agencies, while also dismantling the country's broader climate policy framework – all of which creates uncertainty about the future of CDR development and deployment in the United States. This includes the headline US$3.5 billion DAC Hubs Program, which had awarded only US$1.2 billion of the total to 21 projects by the beginning of 2025. In October 2025, the Department of Energy cancelled 10 of the 21 projects; all were at early stages and represent US$47 million in revoked funds.[49] As of April 2026, initial funding for the two headline projects in the construction phase – the South Texas DAC Hub and Project Cypress in Louisiana – had been restored, but uncertainty remains around the rest of the program's funding. Furthermore, cancellation of funding for earlier-stage projects may undercut the future of the industry.

Annual budget appropriations for government agencies also support CDR research and development, and these funding levels have increased steadily for the past several years. At the Department of Energy, which leads research on novel CDR, funding increased from almost nothing before fiscal year 2020 to US$118 million in fiscal year 2024.[50] While the President's Budget request for fiscal year 2026 aimed to nearly eliminate support for

CDR, Congressional appropriations kept funding for CDR almost unchanged from 2025, demonstrating bipartisan support for the field and maintaining funding for government purchase of CDR, a key demand support mechanism.[51,52] Whether this funding is spent by agencies as directed remains to be seen.

In July 2025, H.R. 1 (the "One Big Beautiful Bill") was enacted, weakening many clean energy tax credits but expanding the 45Q production tax credit for CO_2 storage– which supports DACCS and BECCS along with capture on fossil emission sources. The credit level for utilization of CO_2 was raised to match the credit level for geologic storage of CO_2. Using CO_2 captured by DACCS or BECCS – including use in enhanced oil recovery – now receives the same credit level as dedicated storage: US$180/t$CO_2$ for DACCS and US$85/t$CO_2$ for BECCS.

Despite the 45Q tax credit remaining intact, some companies have already shifted operations elsewhere due to the diminished policy support and continuing uncertainty. At the same time, because CDR policy in the United States has disproportionately supported DAC, these policy reversals have had less impact on other CDR approaches.

Switzerland

Switzerland demonstrates a high level of strategic coherence and innovative leadership in CDR, supported by its strong research institutions and dynamic carbon start-up ecosystem.[53] At the same time, it shows a high level of international engagement in CDR, reflecting the recognition that, as a small country with relatively limited domestic CO_2 storage capacity, meeting its climate targets will require international cooperation. It was among the first countries to explicitly integrate CDR into its long-term climate strategy[54] and to adopt a legally binding greenhouse gas neutrality target by 2050[55] and net-negative emissions after 2050. A national CDR roadmap[56] sets the aspirational goal to capture and store 500,000 tonnes of CO_2 annually from domestic point sources by 2030, with waste-to-energy facilities – where the capture of the biogenic CO_2 component leads to removals – expected to deliver a significant share of this volume. By 2050 Switzerland anticipates deploying 7 million to 9 million tonnes of CDR to counterbalance residual emissions, equivalent to roughly 12%–16% of its 1990 emissions. According to the roadmap, around 2 MtCO_2 would be achieved domestically, primarily through BECCS, while about 5 MtCO_2 would be sourced internationally, largely from DACCS. An additional 1–2 MtCO_2 is earmarked to counterbalance international aviation emissions associated with Switzerland,[57] though it remains unclear whether these removals will come from domestic or international supply.

Switzerland's roadmap prioritizes novel CDR methods, consistent with the country's commitment to position itself as a global hub for novel CDR companies and startups, with Climeworks and Neustark as prominent examples. While the roadmap notes that a broader suite of CDR methods may play a role – and Swiss climate legislation does not impose a binding definition of durability – conventional CDR approaches are treated with caution due to concerns about permanence and potential competition for land and sustainable biomass. Switzerland's LULUCF sector has historically been a net sink,[58] but its sink capacity has declined markedly over the past three decades. Average annual removals were around 4 $MtCO_2$ between 1990 and 1995 and fell to just 0.6 $MtCO_2$ between 2018 and 2023, mirroring a broader downward trend observed throughout Europe.

Beyond target setting, Switzerland's climate-policy framework includes several instruments to incentivize CDR uptake. Financial support for CCS and CDR can be accessed both under the Climate and Innovation Act,[55] for companies submitting net-zero roadmaps, and under the CO_2 Act,[59] for operators covered by the Swiss ETS. Moreover, beginning in 2025, captured and permanently stored CO_2 may be credited towards ETS compliance, strengthening the business case for deployment. Additional circular economy[60] and forestry policies[61] encourage CO_2 storage in long-lived materials such as wood and mineralized concrete by, for example, mandating the deployment of Swiss-grown wood in public buildings. Despite this range of incentives, Switzerland lacks a long-term financing strategy for CDR deployment and targeted incentives to secure market uptake of different CDR methods.

The expansion of CO_2 capture and storage infrastructure represents both a technical and regulatory challenge. CO_2 captured for disposal is legally classified as waste, which does not allow for underground storage and makes cross-border export subject to waste legislation.[62] Moreover, under the Swiss constitution, responsibility for designing CO_2 infrastructure lies primarily with the cantons rather than the federal government.[63] Following a parliamentary mandate[64] in 2025, a new federal framework law will be developed to set national guidelines and harmonized standards, while leaving implementation to the cantons. This situation may complicate implementation of a sectoral agreement,[65] which obliges all major waste-to-energy plant operators to install at least one CO_2 capture facility by 2030 with a minimum capacity of 100,000 tonnes per year. While domestic solutions to store CO_2 in mineralized concrete are being explored, innovative demonstration projects are investigating potential alternative pathways, such as transporting captured CO_2 from Switzerland to Iceland for in situ mineralization (DemoUpCARMA)[66] and storing CO_2 underground domestically (CiTru).[67]

Internationally, Switzerland has been a pioneer in advancing bilateral cooperation on CDR under Article 6.2 of the Paris Agreement.[68] In June 2025, Switzerland concluded the first CDR-specific agreement under Article 6.2, partnering with Norway to allow the transfer of verified carbon removals between the two countries. As well, in 2023 Switzerland ratified the amendment to Article 6 of the London Protocol, which enables offshore geological storage of CO_2.[69]

Germany

While Germany has long been reluctant to accept the need for CDR and geological CO_2 storage,[24,70] recent reforms to the country's legal framework have led to a significant shift in its climate policy approach. In November 2025, the federal parliament amended the 2010 Carbon Dioxide Storage Act, moving from banning commercial CO_2 transport and storage to allowing offshore storage in Germany's exclusive economic zone, with the exception of marine protected areas. The law also includes an opt-in clause for onshore storage for the federal states (*Bundesländer*). In addition, the federal government aims for the ratification of a resolution of an amendment of the London Protocol to pave the way for transnational CO_2 transport for offshore storage.

These reforms represent an effort to advance a strategic framework for CCS, CCU and CDR under the label "carbon management" to achieve the net emissions reductions targets set out in the Federal Climate Change Act, including the net-zero GHG emissions target for 2045.[71] The law includes a quantified target for net "natural sinks" in the LULUCF sector, historically a net carbon sink. However, since 2013 the sector has undergone a sustained reversal from net sink to net source, a trend that has intensified in recent years. The law also provides for the government to set a quantified target for "technical sinks", or novel CDR. This would make Germany the first country in the European Union with a such a target. Furthermore, Germany is one of the few countries in the world that has already set out in law its long-term intention to achieve net-negative GHG emissions.[72]

In recent years, R&D has played a key role in the country's CDR policy landscape. Two federally funded programmes were set up in 2021: CDRterra and CDRmare. These large-scale research initiatives have been exploring the potential and risks of deploying both land-based and marine CDR. The Olaf Scholz government issued two draft strategies but failed to adopt them before leaving office prematurely in early 2025: a Carbon Management Strategy focusing on CCS and CCU, and a Long-Term Strategy on Negative Emissions (*Langfriststrategie Negativemissionen*) with the aim of clarifying the role of CDR in the country's climate policy framework. The latter is now expected to be adopted during the legislative term that began in 2025, which would lay the groundwork for detailed CDR policies.[73]

Additionally, the government of Friedrich Merz created the first-ever dedicated CDR unit, established within the restructured Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety. Significant funding (€111 million) is allocated to CDR in the 2026 federal budget,[74] of which €98 million is slated for project subsidies and €11.5 million for direct public purchasing of CDR credits. Appropriations of €320 million have already been committed until 2033, and additional positions are expected to be filled for the new unit in the subsequent federal budgets after 2026.

The ongoing integration of CDR into the EU climate policy framework[75] directly influences Germany's CDR policymaking. Undertakings such as the CRCF Regulation, the revision of the LULUCF Regulation, and the planned reform of the EU ETS inform the relevant dimensions of domestic policymaking. The EU Common Agricultural Policy (CAP) enables funding for conventional CDR through Member States' National Strategic Plans.

At the national level, several policy instruments are in place to support conventional CDR. While not specifically targeting CDR, national strategies on forestry, peatland protection and soil protection acknowledge removals as a co-benefit. A continuation of the 2023 Federal Action Plan on Nature-based Solutions for Climate and Biodiversity (€821 million in 2026) focuses on decreasing the gap between current projections for emissions and removals in forests, peatlands and coastal ecosystems, and the net LULUCF targets established in the Federal Climate Law.[76] Policy instruments incentivizing novel CDR are less developed, as grant programmes such as the Federal Fund for Industry and Climate Action and the new industrial decarbonization programme only implicitly cover CDR through funding for the capture, storage and utilization of predominantly fossil CO_2 in industrial sectors.[77]

Box 5.2 Limitations and knowledge gaps

Both the policy typology applied and the policy analysis conducted in this chapter are new for *The State of CDR 3rd Edition*. As a FOAK aggregation and assessment of all CDR-relevant policies – both novel and conventional – across G20 countries and the European Union, it is possible that some policies may have been missed or improperly tagged. This analysis will be improved and refined in future editions.

Additionally, for net targets in the LULUCF sector, the proportion attributable to conventional removal may not always be clear. National GHG inventory categories sum up fluxes of different GHGs per land-use category. This leads to an aggregate number including CO_2 drawdowns both from natural uptake and from CDR, as well as emissions on the same land.

Beyond that, there are many areas where future research is needed. We have conducted a preliminary assessment of policy sequencing across different jurisdictions, but additional research is warranted to do this more systematically and determine the implications of different policy sequences under different types of national circumstances.

5.4 Outlook

Countries that have set net-zero targets have already implicitly included a role for CDR in their climate plans, but many have not communicated the details of how they plan to use CDR to reach those targets. Long-term strategies oriented towards 2050 and beyond, as well as current NDCs focused on 2035, present opportunities for countries to communicate the expected level of conventional and novel CDR needed by these target years based on expected levels of residual emissions at the net-zero target year. More broadly, keeping CDR on the national and international policy agenda depends in many cases on maintaining commitments to net-zero targets.

To enable CDR to scale up to the levels estimated in national targets, countries will need to either begin or continue to develop policies that enable the achievement of those targets. This includes policies to support innovation and scaling to develop the supply of CDR; policies to drive demand for CDR; and foundational policies to create a governance framework for CDR, including rules for quantification of removal, guidelines for community engagement and the minimization of negative environmental impacts.

The application of the policy typology to the novel CDR policy database reveals a focus on supply-side policies, comparatively underdeveloped foundational policymaking and a lack of action incentivizing demand for CDR. However, distinct country approaches can provide useful blueprints, for instance for policy sequencing, for other countries that are in the early stages of CDR policymaking. Countries need to ensure that their climate targets acknowledge the role of CDR alongside steep emissions reductions – and advance a suite of policies to enable progress.

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Long wooden corridor with exposed timber beams. By McKlin

Chapter 6 | Perceptions and communication

Effective deployment of CDR depends on public perceptions and responsible communication to publics and potential adopters. Research reveals that familiarity with CDR remains low, but there are clear conditions for support and lessons for communication.

Key insights

- Public attitudes towards CDR are strongly driven by concerns about the impacts of CDR on ecosystems and biodiversity, the need for good governance, the expectation of co-benefits, trust in relevant actors, broader values and beliefs and a preference for low costs and financial benefits.
- Peer-reviewed perceptions research has increased significantly since *The State of CDR 2nd Edition*. The focus of that literature has shifted from drivers of attitudes towards CDR with an already existing strong evidence base and more theoretical considations to less-studied, more practical aspects.
- New lessons for responsible communication of CDR include providing guidance, training and administrative support to adopters such as farmers; communicating inclusively through education and structured stakeholder dialogue; developing local, trusted and context-aware approaches to communication of CDR; and communicating stable, fair and transparent long-term policy signals.
- Recent developments in CDR communication show declining trends, partly tied to decreasing attention to climate overall. Newspaper coverage of CDR has decreased since 2021 by 24% annually. Most newspaper articles follow recommendations for responsible communication of CDR, for example by emphasizing the need to reduce emissions and not framing CDR as an alternative solution to mitigating climate change.
- Attention to CDR has decreased since 2023 by 16% annually on Twitter/X but fluctuated at a high level on Reddit. Sentiments in CDR posts differ significantly between three social media platforms, being more positive on Bluesky and more negative on Reddit, compared to Twitter/X.
- Learnings from perceptions and communications research can be applied to design community engagement for project siting and thus enable equitable and sustainable CDR deployment.

Whether CDR deployment can be successful at scale depends on public understanding and support as well as technological advances. This chapter assesses the peer-reviewed literature to distil important factors driving attitudes towards CDR and conditions under which CDR deployment is acceptable. It also provides updated and expanded analyses of how newspaper sources are communicating about CDR and how users on social media engage with CDR topics.

6.1 Why public perceptions matter

Public perceptions and communication play a crucial role in the development, scaling and adoption of carbon removal methods. Previous research on renewable energy and carbon management technologies demonstrates that communities may block or delay projects they perceive as risky, unfair, environmentally damaging or imposed without proper engagement.[1–4] On the other hand, community engagement that provides space for deliberation and the raising of concerns can increase support.[5–8] Research shows that public attitudes are driven not only by technical assessments but also by social and psychological factors such as trust in those deploying the methods, perceived risks and benefits[9,10] and the sociotechnical contexts in which implementation ultimately unfolds.[11–13] The development of CDR will, therefore, depend not only on technological advances but also on effective societal engagement and responsible communication. Indeed, this is already visible in real-world examples of CDR development (see Box 6.1).

Box 6.1 Public engagement case studies

- An examination of public engagement in the Dominican Republic focused on how a project sought to build collaboration and participation from the outset in a climate-vulnerable coastal community.[14] By documenting local responses over two years, it identified local concerns and development priorities that, in turn, informed outreach and community development efforts around a proposed coastal enhanced weathering trial. It also showed how ideas of climate justice, vulnerability and local socioeconomic development shaped how people understood and engaged with the project. The case illustrates how governance choices, outreach and community development efforts can influence both the social acceptance and practical trajectory of CDR trials.

- Research in the United Kingdom showed how local communities actively shaped the debate around an ocean alkalinity enhancement field trial, challenging how scientists and developers defined both the experiment and the "public" it was meant to benefit.[15] Through protests and place-based actions, people around St. Ives Bay reframed the trial as something that would directly affect their livelihoods, ecosystems and everyday coastal life, rather than a purely scientific or benign research trial. The case highlights how public engagement can surface overlooked risks, question who gets to speak for the public and influence how CDR demonstrations are designed and governed.

- A study in Iceland looked at how local communities responded to a carbon storage project involving some CO_2 captured from ambient air, which serves global climate goals but offers few clear local benefits, particularly in terms of economic opportunities.[16] Focusing on an international CCS hub in Iceland, it revealed how concerns about risk, fairness and importing other countries' emissions shaped public unease and resistance. The case underscores how meaningful engagement, especially listening to local framings and discussing local concerns, matters for building trust and dialogue around CDR projects.

Two aspects of perceptions of and communication about CDR are especially important for future CDR development.

First, publics can organize political support for or opposition to CDR, whether through direct actions or expressions of either approval or disapproval. CDR deployment can only scale under a "social licence to operate", which requires some active support or at least passive acceptance from various societal groups. Public attitudes can therefore shape broader debates around CDR, for example in relation to legislative processes at a national level or in response to specific CDR projects in local contexts. In more general or national-level political debates, a better understanding of public perceptions and relevant concerns can inform the development of well-designed policies and ensure that any investments and deployments align with societal values.[17] Publics can also hold policymakers and businesses accountable for delivering on net-zero targets. The broader sense that segments of the public are predisposed against CDR can motivate further opposition or disengagement, as well as discourage participation by investors or policymakers.[13]

In the context of local CDR projects, negative attitudes and risk perceptions can motivate criticism of proposed deployment, for example leading to rejection of permits in permitting processes or conflict in planning boards. Engaging local populations early on in planning processes can help adapt CDR deployment to local needs and circumstances and ensure that major concerns are addressed. Local communities provide important knowledge about historical and social contexts.[15] Apart from being normatively advisable, proactive engagement of local populations has been shown to be beneficial for environmental and social outcomes.[18] Failure to meaningfully engage with communities might lead to backlash, as the examples of other novel technologies such as renewable energy and CCS have shown[5,19–21] (see Box 6.1).

Second, specific CDR methods require that certain groups adopt technologies or change their practices. For instance, CDR methods that involve farming or forestry – such as soil carbon sequestration, enhanced weathering or biochar soil amendment – require that farmers or landowners directly participate in schemes and implement changes in their land management practices.[22,23] Successfully communicating potential co-benefits and risks can mobilize those groups to adopt CDR practices. However, without well-designed engagement, communities that tend to distrust new technologies and practices – viewing them as potentially risky, unfair or undesirable – may push back on their adoption or force delays in their implementation. Furthermore, potential adopters may perceive the opportunities and challenges of such innovations differently from what technology developers or policymakers might expect – and thus may not adopt CDR as envisioned. While the importance of public engagement and support within broader decision-making processes might depend on the political system – it can be less crucial in non-democratic states – the need to engage potential adopters and other involved parties is valid across different political and social contexts. The various societal groups and modes of engagement that may shape the future of CDR development (see Figure 6.1) depend on the specific CDR method proposed and the political system in which it will operate. Aside from substantive, instrumental and normative reasons for public engagement, research has shown that publics want to be engaged to various degrees.[24,25] Responsible communication and community engagement, therefore, becomes essential to building trust, addressing concerns and enabling carbon removal to scale in ways that are effective, sustainable and publicly supported.

Societal groups and modes of engagement shaping CDR outcomes

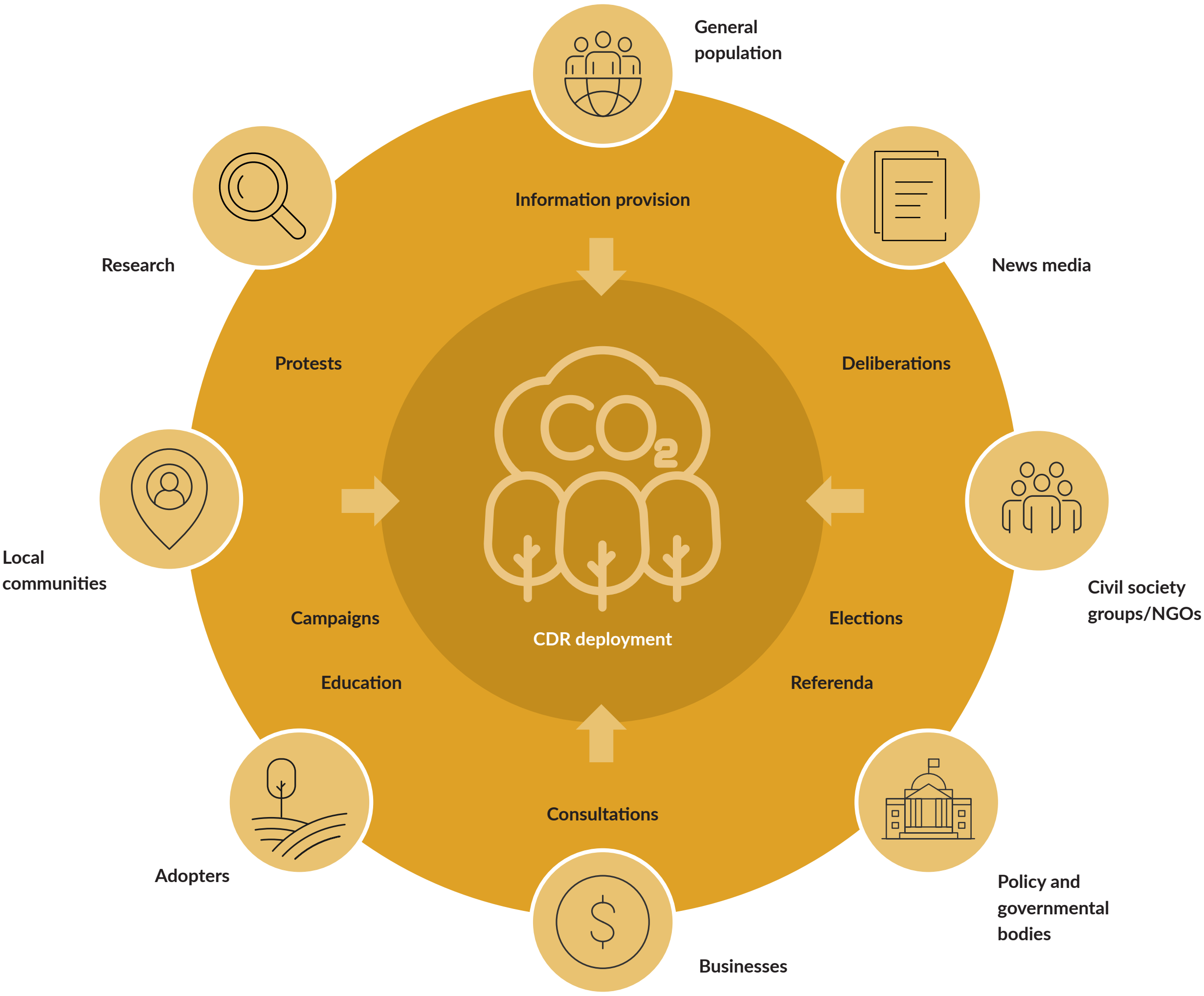


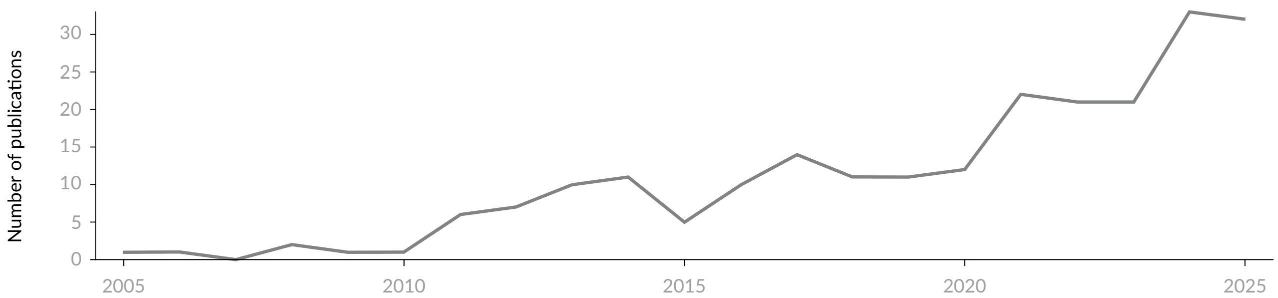
__Figure 6.1__ A non-exhaustive map of societal groups or sectors and modes of engagement important for CDR deployment.

6.2 Literature assessment: what do we know about perceptions of CDR?

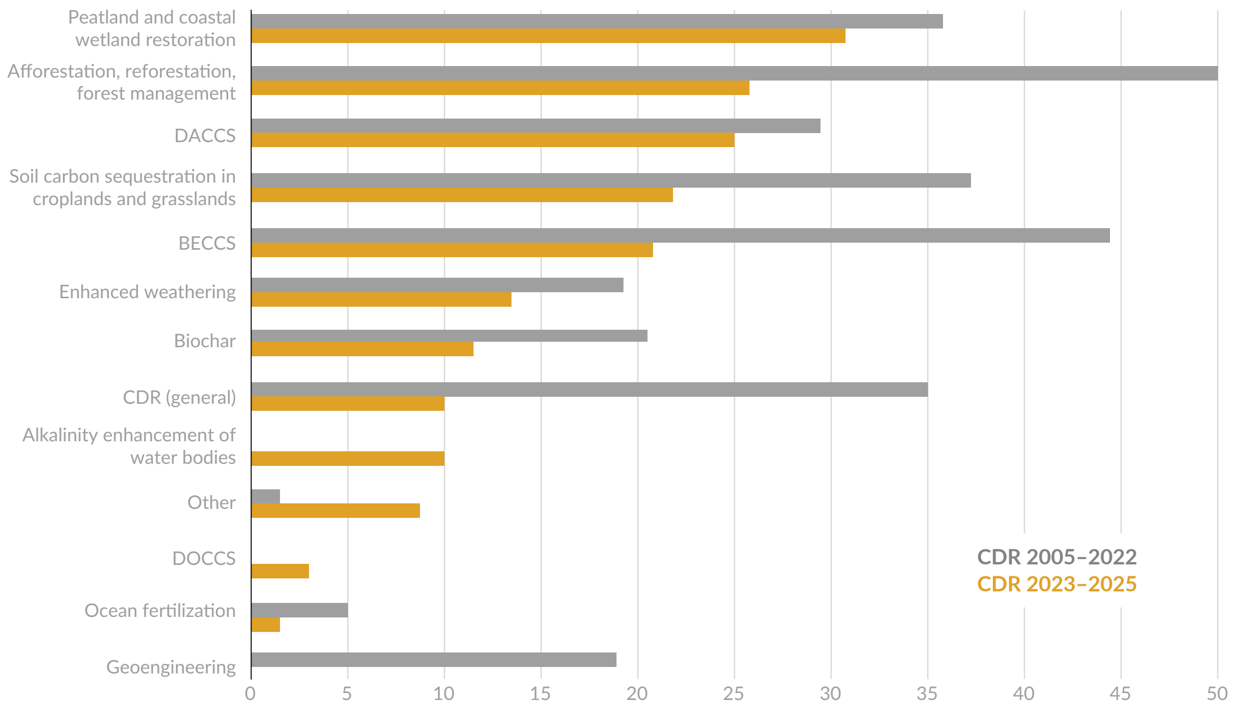
To assess the state of knowledge on perceptions of CDR, we update the systematic review of the academic literature on public perceptions and communication that we undertook during *The State of CDR 2nd Edition*. This review draws on empirical research using various methods including but not limited to surveys, focus groups, deliberative workshops, interviews and media analyses (see the Technical Annex). We find a notable increase in the annual volume of publications, with the numbers for both 2024 and 2025 about 50% higher than the average for 2021 to 2023 (see Figure 6.2). Furthermore, the focus of the studies is changing from a general CDR or geoengineering framing to one that includes a comparative analysis of multiple CDR methods within a single research design. We also observe a higher share of studies focusing on DACCS, coastal wetland restoration and alkalinity enhancement of water bodies.

Overview of studies on perceptions of CDR

a) Number of publications on perceptions of CDR, 2005–2025



b) Number of publications by CDR method



c) Number of perception studies by region of analysis

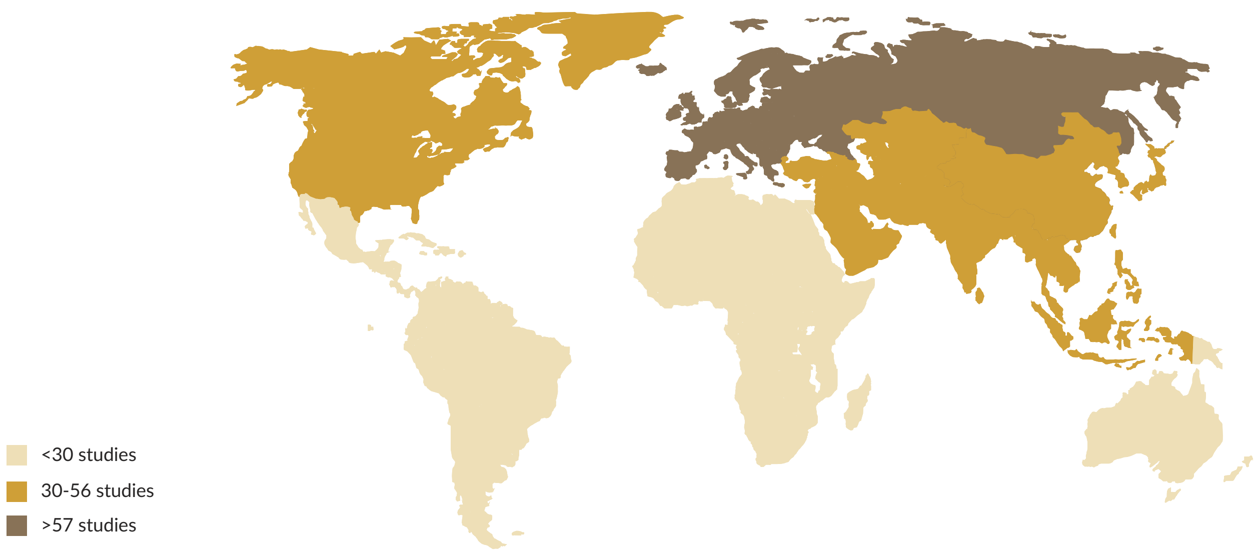


Figure 6.2 *(a) CDR perceptions studies over time and (b) number of publications focusing on different CDR methods. These numbers sum to more than the total number of studies, as many studies cover several CDR methods. (c) Number of publications by the region(s) they focus on. An additional 48 studies are international in coverage and not displayed in panel (c).*

Studies report low to moderate levels of public awareness, familiarity or knowledge about CDR. Surveys often find low familiarity with many CDR methods, with afforestation and reforestation being the most well-known.[26,27] However, it is difficult to compare numbers on public awareness, familiarity and knowledge because the number of articles presenting such data remains low, and studies often measure these factors and report aggregate results in various ways. An immediate implication of low familiarity is that opinions expressed in surveys might be highly susceptible to change.

Factors driving attitudes and conditions for deployment

Studies on public perceptions reveal the reasonings that underlie attitudes towards CDR methods. Assessment of the evidence base reveals 14 distinct "factors" driving public attitudes towards CDR and 12 distinct "conditions" for deployment of CDR (some indicators are both factors and conditions) (see Figure 6.3). Our assessment found 266 pieces of evidence on factors and 174 pieces of evidence on conditions across 75 papers published between June 2023 and December 2025 (see the Technical Annex). This marks a significant increase in peer-reviewed perceptions research since *The State of CDR 2nd Edition* and reveals several new developments.

Evidence on drivers of attitudes and conditions for deployment

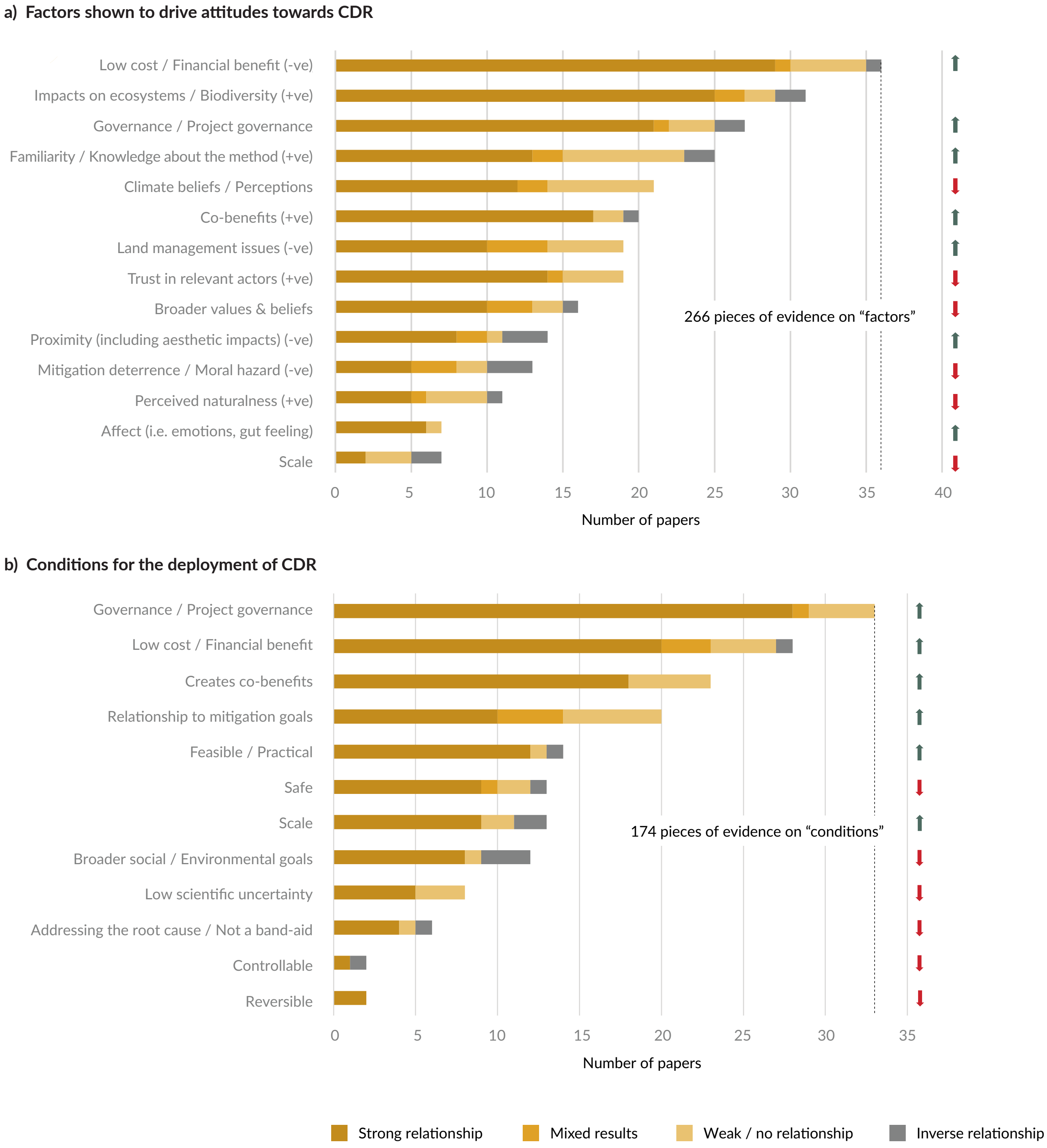


Figure 6.3 *(a) Factors shown to drive attitudes towards CDR and (b) identified conditions for the deployment of CDR, from the peer-reviewed, English-language literature on public perceptions from June 2023 to December 2025 (75 papers). Papers were scored according to whether they provide empirical evidence for a strong relationship between the factor or condition and public attitudes, mixed results, a weak relationship/no relationship or an inverse relationship. Where appropriate, the direction of the relationship is labelled +ve (positive) or -ve (negative). Pieces of evidence = total number of papers discussing the listed factors or conditions (most papers cover more than one topic). Upward arrows = higher rank order according to assessment of pieces of evidence compared to The State of CDR 2nd Edition assessment; downward arrows = lower rank order according to assessment of pieces of evidence compared to 2nd Edition assessment.*

Several factors driving public attitudes towards CDR and conditions for deployment have received proportionately more attention since 2023 than before it, while others have received proportionately less attention. Notably, since 2023, costs and financial benefits, good governance, and co-benefits are among the most-studied factors and conditions, having previously received less attention. Concern about the impacts of CDR on ecosystems and biodiversity remains the second most-studied factor. Among the conditions, the connection of CDR to broader social and environmental goals remains only moderately studied. Other factors that were previously among the most studied have since received less attention, notably perceived naturalness (how "natural", as opposed to "technological", a CDR method is seen to be), mitigation deterrence or moral hazard (the risk that CDR delays emissions reductions) and broader values and beliefs (such as cultural worldviews). Similarly, other conditions that were previously among the most studied have since received less attention – notably safety, controllability, the desire for low scientific uncertainty and the need to address the root causes of climate change. These shifts reflect a need to broaden understanding by focusing on less-studied factors and conditions. Moreover, it reflects a shift from theoretical considerations to practical ones, as an increasing number of CDR approaches are becoming technologically mature, commercially viable and closer to broad deployment.

Overall, the evidence shows that multiple issues strongly drive public attitudes towards CDR including low costs and financial benefits, concerns about the impacts of CDR on ecosystems and biodiversity, good governance, the prospects of co-benefits, trust in relevant actors and broader values and beliefs. Evidence remains mixed on familiarity and knowledge about CDR methods, beliefs about climate change, land management issues and mitigation deterrence or moral hazard.

Lessons for responsible communication

Public engagement is an opportunity to learn about ways in which CDR methods and policies can be made more effective in particular contexts and to make more legitimate decisions by involving those who are affected. However, with levels of awareness about CDR still low, such communication remains a challenge. Would-be communicators about CDR – such as scientists, entrepreneurs, activists, politicians, the media and others – must, therefore, approach the challenge carefully.[28] *The State of CDR 2nd Edition* synthesized seven lessons for responsible communication about CDR from the peer-reviewed literature on perceptions and described them as follows: be careful with terminology; talk about CDR in context; give – and receive – information about CDR; talk about (co-)benefits; also talk about negative attributes; do not weaken support for emission reductions; avoid framing CDR as natural (or otherwise).

A synthesis of the literature published between 2023 and 2025 provides further detail on some of these lessons:

- Increase awareness of CDR. Government media programmes could increase awareness of CDR and improve public learning.[26,29–33]

- Frame issues with care. Framing CDR as "geoengineering" lumps it together with controversial solar radiation modification technologies and can evoke negative sentiments.[34] By contrast, framing CDR in terms of urgency can evoke both positive and negative emotions, either justifying the use of CDR or raising concerns that it may distract from the need for emissions reductions, and therefore requires caution.[35]

- Provide balanced communication. Communicate what is known and acknowledge what is not known,[36] including about risks, benefits and the scale of CDR required in domestic contexts.[24,37–40] Make data from field trials readily accessible.[33]

- Facilitate dialogue. More and different kinds of dialogue[25] are needed among stakeholders in general[41,42] – and with those located in different regions in particular[43,44] – to offer alternative framings, raise important concerns and considerations and strengthen decision-making.[45]

In addition, three new lessons have been drawn from the literature published between 2023 and 2025 for *The State of CDR 3rd Edition*. First, groups with a stake in CDR methods, such as farmers, should be provided with tailored, context-specific guidance – delivered through trained advisors – paired with practical training in carbon-focused land management, dedicated time and resources for on-farm adaptation, and hands-on support with scheme administration.[46–48] Similarly, CDR policy processes should be developed as inclusive, participatory systems that actively engage marginalized and vulnerable groups – supported by accessible, context-appropriate education – so they can meaningfully contribute to shaping fair and effective regulations.[14,49] Second, CDR should be communicated through clear, stable and transparent policy signals that reduce uncertainty – by clarifying long-term benefits, confirming sustained public support and funding and explicitly defining fair and inclusive carbon rights within robust regulatory frameworks.[50–52] Third, CDR communication should be positioned as a coordinated, interdisciplinary effort that combines locally grounded impact evidence, strong interpersonal engagement skills and trusted community messengers – while explicitly addressing the social, behavioural and political contexts shaping public responses.[53–57]

6.3 Empirical analysis of communication about CDR

Responsible communication of CDR in news media

The news media, with their broad reach, shape perceptions of climate change, influencing the actions that individuals and societies take and the policies they choose to support.[58,59] While radio and television broadcasts are beginning to include stories about CDR, we are focusing solely on newspapers in this section, summarizing recent research and analysing how CDR is represented in newspaper articles. With their ability to disseminate information widely, newspapers can influence government agendas and shape public opinions and attitudes. Because people have little prior knowledge on many CDR methods, their role in opinion formation around CDR is critical.

There has been much research into news media portrayals of climate change.[60,61] That includes studies of climate denial discourses and "false balance" in reporting, which occurs when media, in an effort to be "fair", presents each side as equally credible despite evidence favouring one position.[62,63] In the past 15 years, studies on media representations and discourses on CDR and adjacent technologies have emerged. This scholarship often lumps together CDR with climate mitigation technologies such as fossil CCS, or groups them under umbrella concepts like "geoengineering" or "climate engineering".[64–68] The analyses thus often lack nuance regarding the specificities of individual methods.

A considerable body of literature has examined media coverage of both CCU and CCS.[69–77] Analyses of how media report about CDR are fewer and are focused on a small number of CDR methods, with multi-method and multi-country analyses remaining scant. These include analyses of media coverage of BECCS,[53,78] DACCS,[79] restoration of coastal and marine ecosystems, afforestation and related practices,[80–82] and biochar.[45,45] Studies often provide insights into the storylines, frames and narratives used in media coverage on selected CDR methods, for example finding that the use of particular frames is influenced by the political leaning of media outlets[45] and the actors (e.g. scientists, industry or politicians) involved in presenting them.[53] Studies have also traced how framings of CDR can change over time, which has been observed in media representations of DACCS in Europe, where a shift from conflict frames to frames emphasizing co-benefits can be detected.[79] Furthermore, the intensity of media coverage of CDR has been shown to vary over time and to be tied to specific events such as climate summits[45] and the consideration of specific CDR methods, like DACCS, in IPCC reports.[79] Geographically, the scholarship on media communication about specific CDR methods has been concentrated in a few European countries, particularly the United Kingdom[45,45,53,81] and Nordic nations,[78] and in North America.[79]

We update the analysis of CDR in news articles established in the 2nd Edition. Our data is based on a search for CDR keywords in the LexisNexis Newspapers and Wires database, followed by an automated screening and classification process using pre-trained CDR machine-learning classifers.[83] Further methodological information is available in the Technical Annex to this chapter.

The data shows a steady increase in the number of mentions of CDR methods in newspaper articles over time, punctuated by reporting tied to COP events (see Figure 6.4). A wave of articles was published in the run-up to COP26 in Glasgow in 2021, a period during which "net zero" entered the public discourse and attention started to turn to the types of methods that could be used to reach it. Still, there is a longer history of CDR discourse, particularly going back to early discussions on how forests should be integrated into the Paris Agreement.[84] Since 2021, the volume of published newspaper articles has decreased substantially by around 24% annually. This is a much steeper downward trend than the decrease observed in the Media and Climate Change Observatory data on the coverage of climate change in media sources across the world,[85] with only 12% annually. As a result, by 2025, the volume of CDR articles had fallen to its lowest level in seven years.

News articles mentioning CDR by method, 2005–2025

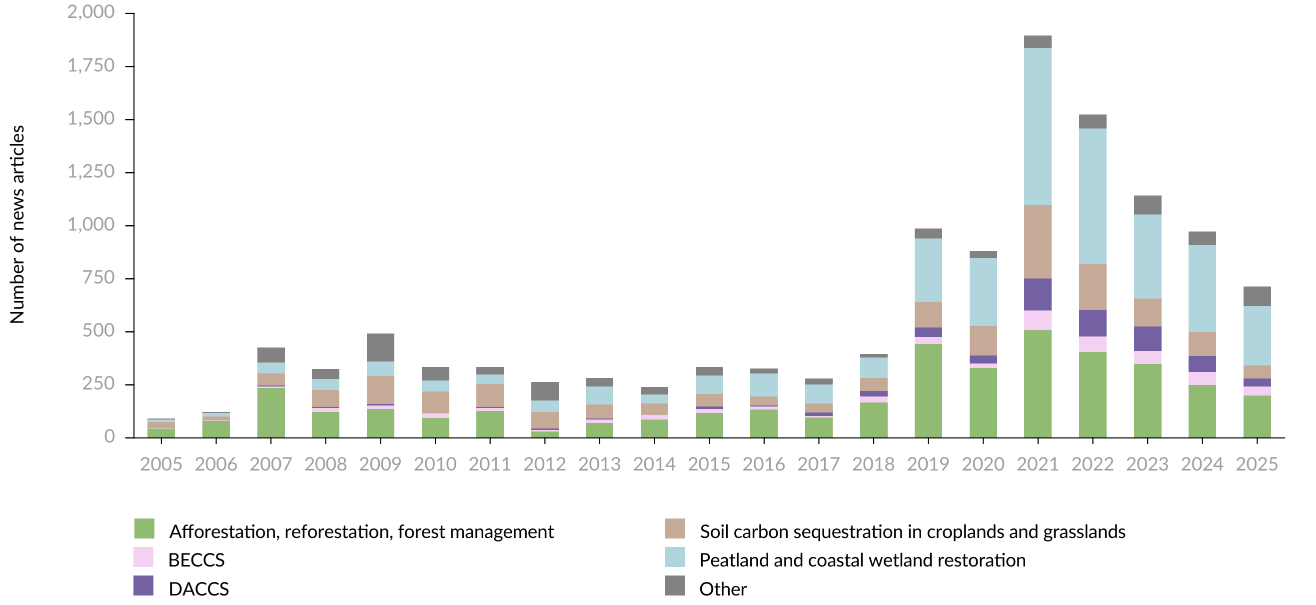


Figure 6.4 *The number of news articles per year that mention a particular CDR method (see the Technical Annex for details on the analysis). The "other" category comprises ocean fertilization, enhanced weathering and biochar soil amendment.*

The literature[28] emphasizes challenges in communicating about CDR and mirrors those – such as low public awareness – that arise when communicating about other areas of science and public policy. Because public awareness is low, the way in which newspapers frame and describe CDR methods can strongly influence how they are perceived and spur either opposition or support when they are deployed. Suggestions include never framing CDR as a substitute for emissions reductions and avoiding framing these technologies as either "natural" or "unnatural". As well, care should be taken in how they are described relative to other technologies and actions such as fossil CCS or adaptation (see Section 6.2).

Here we closely examine a sample of articles from eight major newspapers in the United States, the United Kingdom and Australia, covering primarily DACCS, BECCS, afforestation and reforestation, soil carbon sequestration and "general" discussions of CDR not linked to any specific method. We coded articles on whether they adhere to the recommendations mentioned above (see the Technical Annex). We find that most articles do, indeed, emphasize the need to reduce emissions, with over three-quarters mentioning at least some key sources of emissions that would need to be addressed (see Figure 6.5). The framing of CDR as an explicit alternative to reducing emissions is relatively uncommon in our sample (accounting for less than 5% of articles). On the other hand, we do find many examples of articles that make some CDR approaches appear more attractive through a "natural" framing (25%), or less attractive through an "unnatural" framing (60%). As expected, there is a tendency to deploy unnatural framings more in the case of novel CDR methods (78%). Perceived "naturalness" is known to increase acceptance of CDR, whereas perceived “tampering with nature” is known to lower acceptance. However, the line separating a “natural” from an “unnatural” method is arbitrary and diverts attention from the actual qualities of CDR methods.[28]

Assessment of newspaper articles along different dimensions of responsible communication

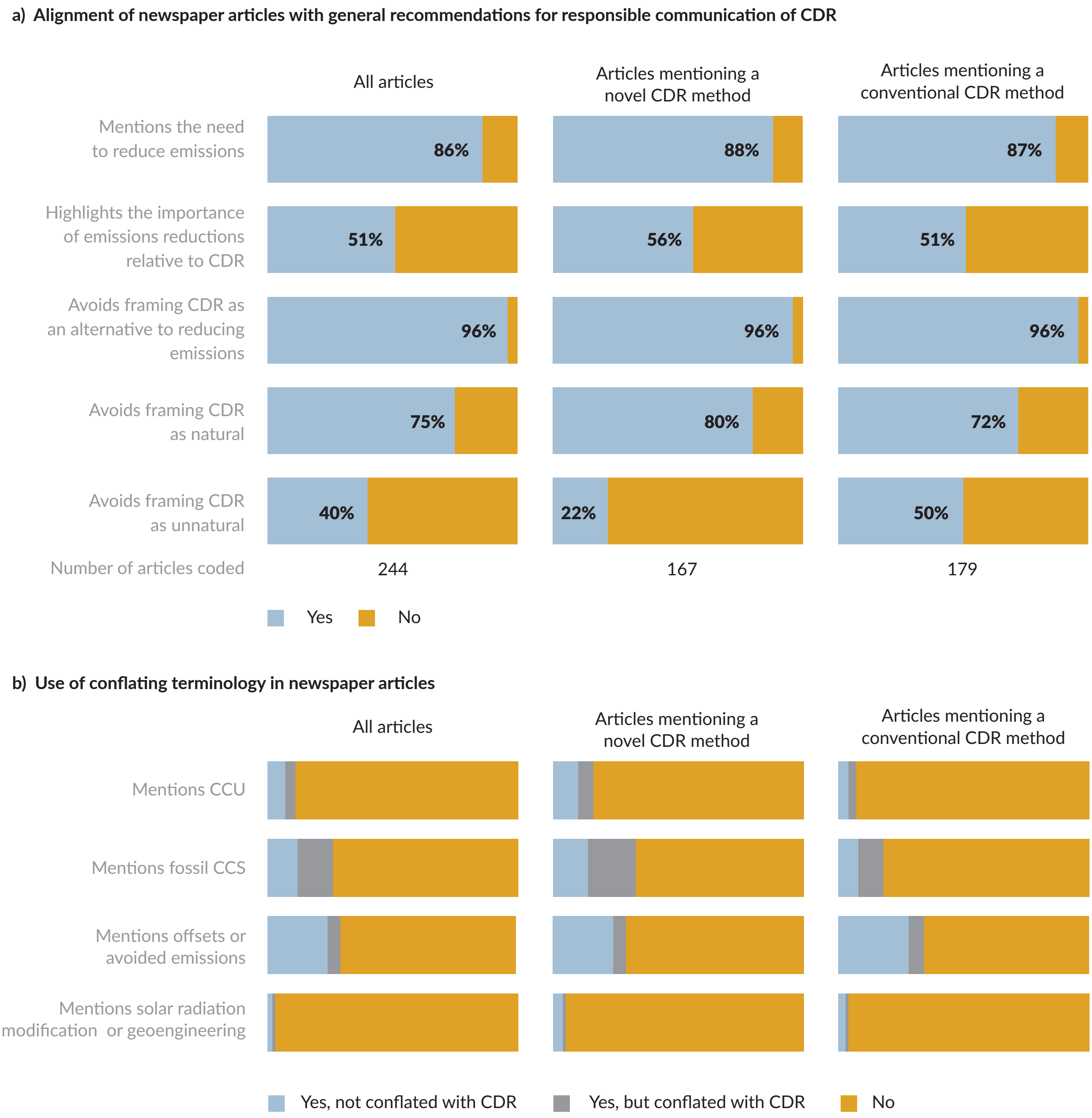


Figure 6.5 *Shares of analysed newspaper articles that (a) align with recommendations for responsible communication of CDR and (b) use conflating terminology. Panel (b) differentiates between articles that discuss CDR alongside non-CDR technologies (such as fossil CCS or avoided emissions) and whether they clearly distinguish these technology types (blue) or fail to do so (grey). Note: articles mentioning more than one technology are counted more than once.*

How well do articles distinguish CDR from other mitigation actions? Researchers distinguish CDR from other types of mitigation, such as fossil CCS (see Chapter 1). But newspaper articles do not always make such differences clear. We find that when fossil CCS is mentioned (which occurs in 25% of our sample), it is clearly distinguished from CDR in just over half of the cases. One example is when an article fails to note that in the case of CDR, the CO_2 must be captured from the atmosphere (see Figure 6.4). CCU/S, offsets or avoided emissions projects, and solar radiation modification are other areas of potential conceptual overlap. Again, we see that when these methods are mentioned, articles often do not clearly distinguish them from CDR.

This analysis suggests that journalists and editors have room to deepen their understanding of CDR and improve their reporting. While framings of CDR as an alternative to mitigation are largely – but not entirely – avoided, problematic use of nature versus technology framings and a lack of conceptual clarity with respect to other types of climate change mitigation should be corrected. These issues are not trivial insofar as interest groups, such as oil and gas companies, are known to emphasize their climate credentials by engaging in "natural climate solutions" and promoting fossil CCS projects, many of which are associated with enhanced oil recovery practices.[86] Building public trust in CDR will require guarding against such obfuscations across multiple channels of communication.

CDR mentions and sentiments on social media

Communication on social media provides a complementary perspective to CDR communication in newspapers and can serve as a direct source of information to learn about people's attitudes towards new technologies and practices. While news media provide professionally written and edited content, social media comprises content from a diverse range of users. However, there are overlaps, as journalists are often active on social media and users share content from media websites on social media. The previous editions of *The State of CDR* provided insight into several topics including: the rapid growth of user engagement with CDR on Twitter/X; the sentiments attached to comments on CDR; the patterns of engagement across geographies; and the types of users engaging with CDR communication on the platform. These insights are also discussed in more detail in the academic literature.[34,87] The 3rd Edition updates the Twitter/X analysis, focusing on English-language posts that mention CDR, and draws comparisons with two other social media platforms – Bluesky and Reddit – that have publicly accessible data and different user profiles.

Recent years have seen massive shifts in public social media communication patterns, driven by several main developments. First, Elon Musk's acquisition and subsequent modification of Twitter/X led some users – especially, but not only, from the environmental community[88] – to leave the platform in favour of alternatives, while other users remained and engaged more strongly. Second, several new Twitter/X-like social media platforms have been established, namely Bluesky and Threads (the latter by Facebook parent company Meta). Third, platforms with new media formats and concepts have gained in popularity, including Instagram and TikTok, which are built around pictures and short video clips, but also professional networks such as LinkedIn, which are increasingly used for public debates and announcements. Established social networks like Facebook still play a major role, but most of their communication is not publicly oriented and instead occurs through direct or group-based channels. One recent Facebook-based study found little influence of CDR-related messaging.[89] Only messages with more extreme framings or presented by more extreme messengers had any influence at all. Finally, policies to reduce or control the prevalence of misinformation on social media have been reversed in recent years. Especially for climate-related topics, this poses a threat to the integrity and accuracy of information and the foundations of deliberative debate, potentially leading to the spread of climate denial and pushback to climate solutions.[90,91]

These developments have implications for analyses of social media messages. A few years ago, Twitter/X was the go-to platform for researchers wanting to conduct such analyses – due both to high data accessibility and the strong representation of socially, economically and politically influential people of various political leanings. Today, the publicly accessible social media landscape has become more polarized and fragmented, infused by politics, culture wars and generational differences. Furthermore, parent companies of social media sites are more frequently restricting access to the data because it is a lucrative resource for training AI models.

These changes, in turn, have led us to broaden our analysis of the social media landscape in *The State of CDR 3rd Edition*. In addition to evaluating data from Twitter/X, as was done in previous editions, we employed the same search strategy to review data from Bluesky and Reddit, as both allow access to publicly available comments and posts (see the Technical Annex for further details on methodology). For Bluesky, which now hosts a significant community of environmental researchers, we filtered a large collection of all posts from 2023 to 2024[92] to find about 6,500 posts mentioning CDR. This is, of course, much less when compared to Twitter/X's up to 100,000 relevant posts per year. However, in relation to the size of its user base, the number of CDR-related posts per user is six times as large as for Twitter/X. Reddit data was collected from all climate-related subreddits, resulting in 12,500 CDR-related submissions and comments from 2010 to 2025.

User engagement with CDR on Twitter/X increased between 2010 and 2022 (see Figure 6.6a). From 2023 onwards, the number of posts mentioning CDR steadily declines. However, compared to the decrease in posts mentioning "climate change" at 24% annually between 2023 and 2025, this decrease in CDR mentions is less strong at 16% annually. While about one-third of the engagement is related to general CDR keywords, the rest mentions specific CDR methods. The share of posts related to DACCS has increased noticeably in recent years, though most of the methods-specific posts relate to conventional CDR methods, such as afforestation and reforestation, soil carbon sequestration and peatland and coastal wetland restoration. By comparison, novel CDR approaches – such as biochar soil amendment, enhanced weathering and BECCS – continue to receive minimal attention. While mentions of most CDR methods decreased on Twitter/X after 2022, mentions of afforestation and reforestation slightly increased. Mentions remained relatively stable for some of the other CDR methods that receive relatively less attention, such as biochar and enhanced weathering.

In comparison, the engagement level of Reddit users fluctuates more strongly over time (see Figure 6.6b), with peaks in 2019 (coinciding with the peak of climate protests by Fridays for Future and adjacent groups), 2023 and 2024. Most Reddit posts mention CDR in general, followed by afforestation, DACCS and enhanced weathering. Compared to Twitter/X data, novel CDR methods receive relatively more attention in Reddit posts, particularly DACCS and enhanced weathering. Soil carbon sequestration and peatland and coastal wetland restoration receive less attention on Reddit. Data from Bluesky cannot yet be used to analyse developments over time, given its more recent establishment in 2023 (compared to Twitter in 2006 and Reddit in 2005). Still, the share of posts mentioning CDR in general, and afforestation and reforestation in particular, is even larger on Bluesky than on the other platforms. But even on Bluesky, other specific CDR methods are only mentioned infrequently.

Overall, sentiment on Twitter/X towards CDR is more positive (24%) than negative (14%), though a majority of posts are neutral (see Figure 6.6c). Some specific CDR methods are, however, more negatively discussed (e.g. ocean fertilization) while others are associated with much more positive sentiment (e.g. afforestation and reforestation, biochar and peatland and coastal wetland restoration). Overall, sentiments for all methods, except ocean fertilization, are net positive on Twitter/X. The share of both negative and positive sentiments has increased over time, pointing to increasingly polarized debates on CDR topics along with a potentially greater level of nuance and understanding. Updated sentiment data from 2022 to 2025 exhibit very similar patterns to those reported in *The State of CDR 2nd Edition*. The main difference is that the share of positive sentiments has increased for some CDR methods by around 5–10 percentage points. However, this trend could also be driven by increases in emotional engagement on social media, as this is boosted by algorithmic feedback loops.[93,94]

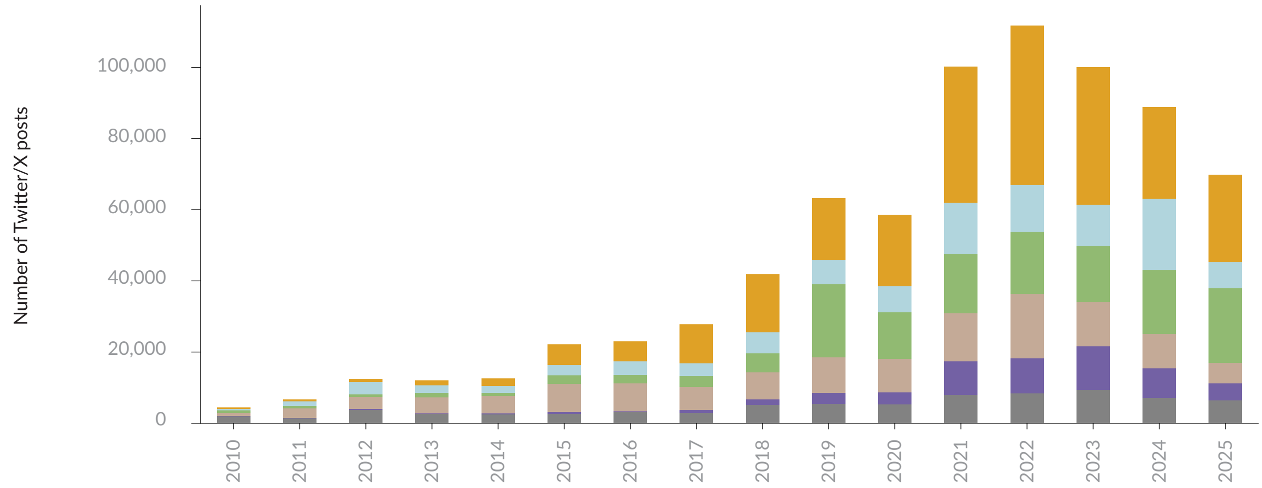
Sentiments about CDR expressed on Reddit are much more negative (25%) and less positive (11%) compared to Twitter/X, though the two are similar in that most posts reflect more neutral sentiments. There is also less variation between sentiment shares for different CDR methods on Reddit. For example, for afforestation and reforestation, there are more posts with negative than positive sentiments on Reddit, in contrast to being overwhelmingly positive on the other platforms. In fact, the only method for which there are more positive than negative sentiments on Reddit is enhanced weathering.

Of the three social media platforms included in this analysis, it is Bluesky's users who tend to engage most positively with CDR: 30% of the posts have a positive sentiment versus 23% that are negative. In part, this pattern is driven by the relatively higher share of posts on afforestation and reforestation and its overwhelmingly positive depiction on this platform. At the same time, there is greater variation in sentiment across CDR methods on Bluesky. In contrast to the very positive sentiment about afforestation and reforestation, more novel CDR methods – such as BECCS, ocean fertilization and, to a lesser extent, DACCS – are viewed more negatively. Even soil carbon sequestration is associated with quite negative sentiment on Bluesky. Besides afforestation and reforestation, only enhanced weathering and peatland and coastal wetland restoration are accompanied more by positive than negative sentiments in Bluesky discussions.

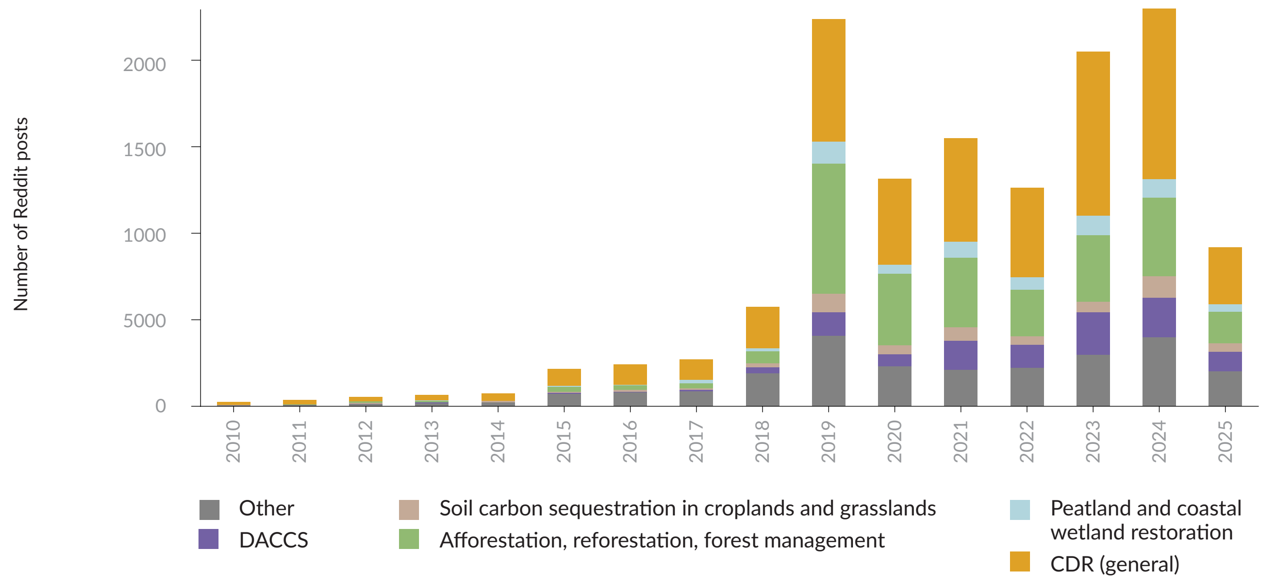
In general, the comparison of different social media platforms reveals similar foci in terms of the CDR methods users tend to engage with. Differences in sentiments between CDR methods have some similarity across platforms, but the overall share of positive and negative comments differs rather strongly between platforms. This may be explained partly by differences in the platforms' discussion cultures, user bases, algorithmic personalization approaches and interaction mechanisms. At the same time, certain CDR methods arouse different sentiments depending on the platform, such as soil carbon sequestration and BECCS, which are perceived much less positively on Bluesky vis-a-vis Twitter/X.

Overview of CDR content on three social media platforms

a) Posts on Twitter/X



b) Posts on Reddit



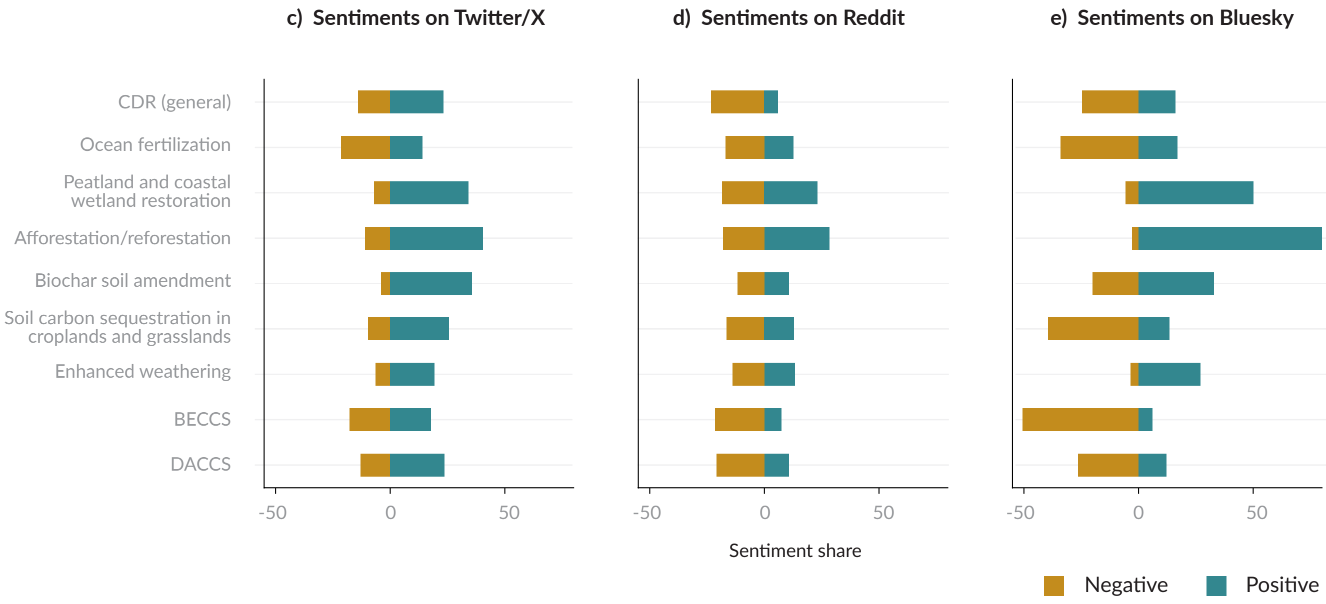


__Figure 6.6__ CDR content and sentiments on Twitter/X, Reddit and Bluesky. Panels (a) and (b) show the engagement of Twitter/X and Reddit users with different CDR methods over time. Panels (c) to (e) display differences in sentiments associated with CDR methods. The category "other" in panel (a) and (b) includes ocean fertilization, enhanced weathering, BECCS and biochar soil amendment.

Box 6.2 Limitations and knowledge gaps

- People's emotions and gut feelings, project scale and proximity – including aesthetic impacts – continue to be relatively understudied factors driving attitudes to CDR, while reversibility continues to be an understudied condition for CDR deployment. For other factors and conditions, results about their influence on perceptions are ambiguous and warrant further research, including familiarity and knowledge about CDR methods, mitigation deterrence or moral hazard, and the relationship of CDR to mitigation.

- Perceptions of certain CDR methods are also understudied, notably agroforestry, durable wood products, bio-oil storage, mineral products, biomass burial, biomass sinking and DOCCS.

- Our analysis focuses on the English-language literature on public perceptions. While this covers a large part of the academic literature, we certainly miss important insights disseminated in other languages, especially from countries with a strong publishing culture in their native language. The restriction of the communication analysis to posts and articles in English also misses trends in other languages and might bias results to perspectives most reflective of the global north.

- Our news media analysis focuses on newspapers and online text media. However, radio and television may also be important media channels through which perceptions of CDR are influenced. Equally, the imagery accompanying CDR reporting is likely to influence how people think about CDR and warrants further research.

- This chapter has taken a first step towards evaluating the extent to which CDR is being communicated in newspaper articles in accordance with lessons for responsible communication synthesized from the peer-reviewed literature on public perceptions. But further research is required to explore this in other regions, languages and forms of media, or through other forms of communication.

- The social media analysis of Reddit and Bluesky data used methods developed for the previous Twitter/X analysis. However, especially on Reddit communication patterns are different, and thus future analyses could take the structure of discussions on the platform into account. Future research could also complement the sentiment analysis with an analysis of actual stances or attitudes towards different CDR methods.

6.4 Outlook

There has been a significant increase in peer-reviewed research on perceptions of CDR since *The State of CDR 2nd Edition*. New evidence shows that low costs and financial benefits, concerns about the impacts of CDR on ecosystems and biodiversity, good governance and project governance, co-benefits, trust in relevant actors and broader values and beliefs are all strong drivers of public attitudes towards CDR. Other factors such as mitigation deterrence and perceived naturalness have received less attention in the most recent literature. The already existing strong evidence examining more theoretical considerations of CDR has thus been expanded to include less-studied, more practical aspects in recent years. New lessons for responsible communication of CDR include communicating farm-specific guidance with training and administrative support; communicating inclusively through education and structured stakeholder dialogue; communicating stable, fair and transparent long-term policy signals; and communicating interdisciplinarily using local, trusted, context-aware approaches.

The chapter identified several decreasing trends in newspaper and social media communication about CDR, which are coinciding with declines in news reporting and online discussions about climate change in general. These factors, together with the continued low awareness found in surveys, are indications that CDR remains a niche topic in public debates. Responsible communication in news media has the potential to increase awareness and strengthen nuanced engagement of publics with the topic, but actual reporting can be improved by avoiding strong nature-versus-technology framings to deliver balanced information on CDR.

Research gaps exist on how perceptions form and evolve over time, especially as CDR moves from the multiple stages of R&D to demonstration and deployment. Project-based research on the perceptions of local communities and potential CDR adopters in real-world settings and how these are embedded and informed by local circumstances and concerns will be especially important for understanding and tailoring future CDR deployment to local and regional contexts. Methods developed in social science research can help build understanding of how and why historical concerns and injustices emerge and are replicated.[25,95,96] This will enable their consideration in discussions around planning, decision-making and community involvement. Research can also help to inform siting decisions and planning processes by better combining geophysical factors with a rich and granular appreciation of socioeconomic considerations.[97]

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Chapter 7

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Carbon Lockdown's Potomac Project in Northern Maryland.
By Ning Zeng

Chapter 7 | Current levels of CDR

Current annual removal from the atmosphere, combining conventional and novel methods, totals around 2,200 $MtCO_2$ per year. The vast majority of this removal comes from afforestation and reforestation. At the same time, another 330 $MtCO_2$ per year, withdrawn from the atmosphere in previous years by trees, is transferred to other forms of durable storage in wood products. Novel CDR activity at 2.0 $MtCO_2$ per year is around 1,000 times smaller than conventional CDR, but it is growing.

Key insights

- Global conventional CDR from afforestation and reforestation has averaged 2,200 $MtCO_2$ per year (with a model range of between 1,800 $MtCO_2$ and 2,600 $MtCO_2$ per year) over the decade from 2014 to 2023. Bookkeeping models, which quantify CO_2 removals and emissions related to land use, and adjusted national inventories broadly agree on this global total.

- The countries that have generated the largest amounts of CDR from afforestation and reforestation from 2014 to 2023 are China, the United States, the European Union, Brazil and the Russian Federation, according to bookkeeping models.

- Some CDR activities involve transferring carbon that was captured in a previous year from one type of storage to another. The transfer of carbon from managed forests to durable wood products averaged 780 $MtCO_2$ per year from 2014 to 2023. After accounting for the CO_2 re-emissions from the decay of existing wood products, the net increase in carbon stored over this period is estimated at 330 $MtCO_2$ per year.

- Activity from novel CDR methods is estimated to total 2.04 $MtCO_2$ globally in 2025, up from 1.4 $MtCO_2$ in 2023. While average annual growth was 36% per year from 2020 to 2025 – led by biochar – the volume from some novel CDR methods declined from 2023 to 2025.

- Biochar (1.46 $MtCO_2$ of which 0.97 $MtCO_2$ is a net transfer of woody carbon) and BECCS (0.51 $MtCO_2$) were the largest contributors to novel CDR activity in 2025, followed by biomass direct storage (0.05 $MtCO_2$). Enhanced weathering (EW) and mineral products contributed roughly equal amounts (0.0038 $MtCO_2$ and 0.0022 $MtCO_2$ respectively).

- Projects operating and under construction suggest a further increase in novel CDR capacity to approximately 8.4 $MtCO_2$ per year by 2030. Despite this, real-world increases in removal in recent years have achieved only 20% of projected capacity.

This chapter presents the latest estimates of current and recent CDR levels, as well as a projection for near-term change in novel CDR capacity based on projects operating or under construction. Our assessment brings together multiple sources of data across CDR methods, harmonized within a consistent framework, to provide a comprehensive and robust estimate of current CDR levels. It provides a brief overview of the assessment framework, with further methodological details available in the Technical Annex. Estimated annual levels of CDR are given for conventional methods (principally afforestation and reforestation) and for novel methods (e.g. biochar, BECCS, DACCS, enhanced weathering, biomass direct storage). Some CDR activities involve transfers of carbon captured in previous years from one form of durable storage (usually woody biomass) to another. We also discuss the pipeline of future CDR in the coming three years based on existing projects and those under construction.

7.1 Methods for estimating current CDR

Criteria for defining CDR

As discussed in Chapter 1, we use the IPCC's definition for what counts as CDR.[1] This definition requires a way to distinguish CDR from natural carbon uptake, which is itself increasing as an indirect consequence of human changes to the environment. Specifically, plant growth is enhanced by the combination of elevated atmospheric CO_2 concentrations, global warming and nitrogen deposition. We include carbon uptake from afforestation, reforestation and forest management activities, but in calculating the resulting CDR we exclude the additional growth caused by environmental changes after establishment. Carbon sinks in unmanaged forests are also fully excluded. Calculating CDR in this way requires models and assumptions, as observations alone are insufficient.

Guided by the definition above, we focus on the annual flux of CO_2 from the atmosphere to durable storage from human activity, minus any stored CO_2 that is subsequently re-released. The wider lifecycle of CDR activities is not included (e.g. construction of facilities and transportation of materials). This aligns with the approach taken by national GHG inventories and the Global Carbon Budget,[2] whereby the emissions from other stages of the project lifecycle are allocated to the sectors in which they occur (e.g. industry and energy). Applied consistently, this approach avoids double-counting emissions and is, in some sense, intuitive: for instance, wind turbines are considered zero-emission in the power sector, while emissions associated with their manufacture, transport, installation and operation are accounted for in the industry and transport sectors.

Still, some definitions of CDR (e.g. Tanzer & Ramirez[3]) require a cradle-to-grave lifecycle assessment (LCA) to ensure that the total overall activity results in net negative emissions. LCA is informative for assessing CDR projects, and the volume of CDR credits issued by current projects is reduced because registries tend to account for lifecycle emissions (see

Box 7.1). It should be noted that our gross estimates do not guarantee net removal at the level of a whole project or system.

As set out in Chapter 1, and consistent with previous editions, we make the following additional choices:

- We exclude BECCS or DACCS projects with EOR. Currently, three such operational facilities capture a total of 0.47 $MtCO_2$ per year.
- We exclude ambient cement recarbonation, currently estimated to remove 700 $MtCO_2$ per year (around a third the size of current CDR from afforestation and reforestation). We do, however, include approaches that directly enhance recarbonation as CDR in the "mineral products" category.
- We include forest growth on abandoned agricultural land as a form of afforestation and reforestation. In many such cases, the forest cover may grow without any direct human intervention, and the abandonment may occur for reasons other than carbon removal. Even so, it can be argued that the abandonment and continuing non-use of the land reflects a human decision.

Estimating current CDR levels

Afforestation, reforestation and forest management

This report uses two largely independent approaches to quantify CDR through forest creation and management during the decade from 2014 to 2023.

The first (primary) approach estimates removals through afforestation and reforestation using data from the three bookkeeping models (BLUE, LUCE, OSCAR) used by the Global Carbon Budget.[2] Bookkeeping models combine information on land-use change, carbon contained in different types of vegetation, and response functions for different types of land-use changes to provide annual estimates of CO_2 removals and emissions from land use since 1700. Employing recent updates in Global Carbon Budget methodology, bookkeeping models incorporate environmental conditions (e.g. atmospheric CO_2 concentrations and climate) prevailing at the time new forests were being established.[4] Any subsequent environmental changes, such as those driven by increases in atmospheric CO_2 after forest establishment, are considered to be part of natural uptake.

The second (complementary) approach provides a global estimate based on aggregated national greenhouse gas inventories (NGHGIs) of emissions and removals in managed forests. Conceptually, NGHGIs include afforestation and reforestation (like bookkeeping models) plus the management of other pre-existing forests. Because NGHGIs typically include both direct human-induced effects (e.g. land-use change) and indirect human-induced effects on plant growth (e.g. CO_2 fertilization), they often report much larger forest carbon sinks than what is typically counted as CDR. To address this, we take CO_2 fluxes reported in NGHGIs under the "managed forest land" category and subtract indirect effects using estimates from dynamic global vegetation models. Acknowledging the different definitions of "anthropogenic sink" between NGHGIs and global models is important and necessary for consistent and comparable assessments of the remaining carbon budget, the timing of net zero and even the definition of net zero itself (e.g. Grassi et al. 2021[5], Allen et al., 2005[6]).

These approaches provide two complementary perspectives on conventional CDR, along with an understanding of regional patterns. Further details on the methods for quantifying conventional CDR can be found in the Technical Annex.

Peatlands, coastal wetlands and soils

Conventional CDR also includes the management of wetlands, such as the restoration of inland peatlands and so-called "blue carbon" sinks like coastal mangrove forests, salt marshes and seagrass meadows. This report does not contain estimates for CDR levels from these methods because they are not included in bookkeeping models. Some NGHGIs report small carbon sinks from wetlands (less than 1 $MtCO_2$ per year), while the United States is the only country that has reported a substantial sink (about 12 $MtCO_2$ per year, up to the year 2022) from vegetated coastal wetlands. However, disentangling the direct CDR component from the total reported carbon sink in wetlands is not currently possible.

Forest soils are included in this report, as they are incorporated in bookkeeping models and in several NGHGIs. However, CDR from soil carbon sequestration in croplands and grasslands are not included in bookkeeping models, and therefore we do not account for these fluxes in this report. Globally, NGHGIs report a net sink of about 500 $MtCO_2$ per year (on average between 2014 and 2023) from croplands and grasslands, mostly in China and India, but it is difficult to separate the CDR component from indirect effects.

Novel methods

Estimates for biochar production volumes are compiled using a survey conducted jointly with the International Biochar Initiative and the US Biochar Initiative. These volumes are converted to CDR estimates following the methodology of Woolf et al. 2021.[7] Because biochar feedstock type can significantly influence carbon content, and therefore CDR per unit biochar, production volumes are categorized by feedstock type, and literature-derived carbon contents are applied to estimate CDR. Biochar decay is accounted for using decay rates dependent on carbon content and soil temperature. Accordingly, reported biochar CDR values are adjusted to subtract CO_2 re-emitted to the atmosphere from the decay of biochar produced in previous years. Uncertainty estimates reflect variability in the reported carbon content of biomass and in soil temperatures used to calculate decay rates. As the survey data is likely incomplete, CDR estimates here should be considered lower bounds. Methodological details and further discussion are provided in the Technical Annex.

Our estimates for other novel CDR methods have been derived from a review of databases – including those maintained by the IEA, CDR.fyi, and Mission Innovation – and registry and crediting platforms such as Isometric and Puro.earth. These privately-operated registries are voluntary rather than mandatory public reporting systems, though certification is increasingly used to enable market participation and credit issuance. Our calculations were verified using a company survey conducted jointly with CDR.fyi. Because our analysis for novel methods relies on company-reported data, it is difficult to quantify uncertainty. Instead, we aim to report conservative values for each novel method that implicitly accounts for uncertainty (see the Technical Annex).

Transfers between durable carbon pools

Several CDR methods involve the transfer of captured atmospheric CO_2 from one carbon pool to another. If the intermediate pool is itself a multi-year store of carbon, there can be a separation in time between the removal from the atmosphere and the ultimate storage. This is especially applicable to woody biomass (in which atmospheric CO_2 is captured during tree growth, which is later harvested and transferred into wood products).

We track these cases as the transfer of carbon from one durable pool to another in a given year, distinct from the removal of CO_2 from the air during that same year. Carbon transfers represent reallocations of previously captured atmospheric carbon and do not generally mean that the carbon was removed from the atmosphere in that year.

The bulk of carbon transfers occur from forests to durable harvested wood products. These are estimated using Food and Agriculture Organization Statistics (FAOSTAT) data on the production of roundwood, sawnwood and wood-based panels. Because these products decay over time, some of the carbon is returned to the atmosphere. The net transfer of carbon into harvested wood products is therefore calculated as the sum of the carbon added to the durable harvested wood products pool minus the carbon returned back to the atmosphere via product decay, based on the IPCC decay functions for each commodity.[8] Note that other, less-durable harvested wood products, such as paper and paperboard, are not counted here as CDR.

FAOSTAT does not provide uncertainty estimates, making it difficult to infer the uncertainty in carbon transfers. Notably, only 15% of the country records reported by FAOSTAT are defined as "official statistics", while around 63% of the data are labelled "estimated values", with the remainder coming from external sources. Additionally, the use of default parameters within the IPCC decay functions further contributes to uncertainty in our estimates.

Novel CDR methods can also involve transfer of woody biomass, with biochar and BECCS being the two principal methods as measured by current and projected future volumes. For biochar, we record the volume of converted carbon in the year of pyrolysis from both woody and annual biomass feedstocks in our estimates of CDR activity (see Figure 7.2).

The biochar made by using woody feedstocks represents a carbon transfer, with the CO_2 capture from the atmosphere having generally occurred in a previous year. There are no current operational BECCS facilities that use woody feedstocks; however, woody biomass has been listed as a feedstock for at least 16 future BECCS-based facilities (IEA, 2025).[9]

7.2 Current conventional CDR

Estimates from the two approaches used in this assessment – bookkeeping models and model-adjusted NGHGIs – show broad agreement and point out that afforestation and reforestation currently account for the bulk of conventional CDR. In particular, CDR in afforestation and reforestation as estimated by bookkeeping models amounts to 2,200 $MtCO_2$ per year (with a range across models from 1,800 $MtCO_2$ to 2,600 $MtCO_2$ per year), averaged from 2014 to 2023. CDR in managed forests estimated by NGHGIs, including both afforestation and reforestation (like bookkeeping models) and management of existing forests, amounts to approximately 2,100 $MtCO_2$ per year (with a standard deviation of 680 $MtCO_2$ per year) between 2014 and 2023. Given the large uncertainties linked to subtracting indirect effects on CO_2 sinks reported in NGHGIs, we provide only a global value of forest CDR derived from the NGHGIs in this report; we do not offer country-specific values. Out of the total estimated CDR of 2,100 $MtCO_2$ per year, the NGHGI subcategory "land converted to forest", which contains all CO_2 fluxes in the first 20 years after land conversion to forest, constitutes approximately 900 $MtCO_2$ per year.

Globally, CDR through afforestation and reforestation as estimated by bookkeeping models increased between 2000 and the mid-2010s and has since remained relatively stable at 2,200 $MtCO_2$ per year (see Figure 7.1a). The long-term CDR increase is predominantly due to China, with additional contributions from Brazil, the Democratic Republic of the Congo, Canada, Mexico and several other countries. Over the same period, CDR rates also decreased in some places, most notably the European Union and the United States. Not all country-level trends are statistically significant. Due to the large uncertainties, it remains difficult to assess the trend in the last ten years (2014 to 2023), where CDR rates appear to have stabilized. However, the real CDR rates are likely lower than our estimates, as bookkeeping models do not account for natural disturbances affecting forest growth and permanence.[10]

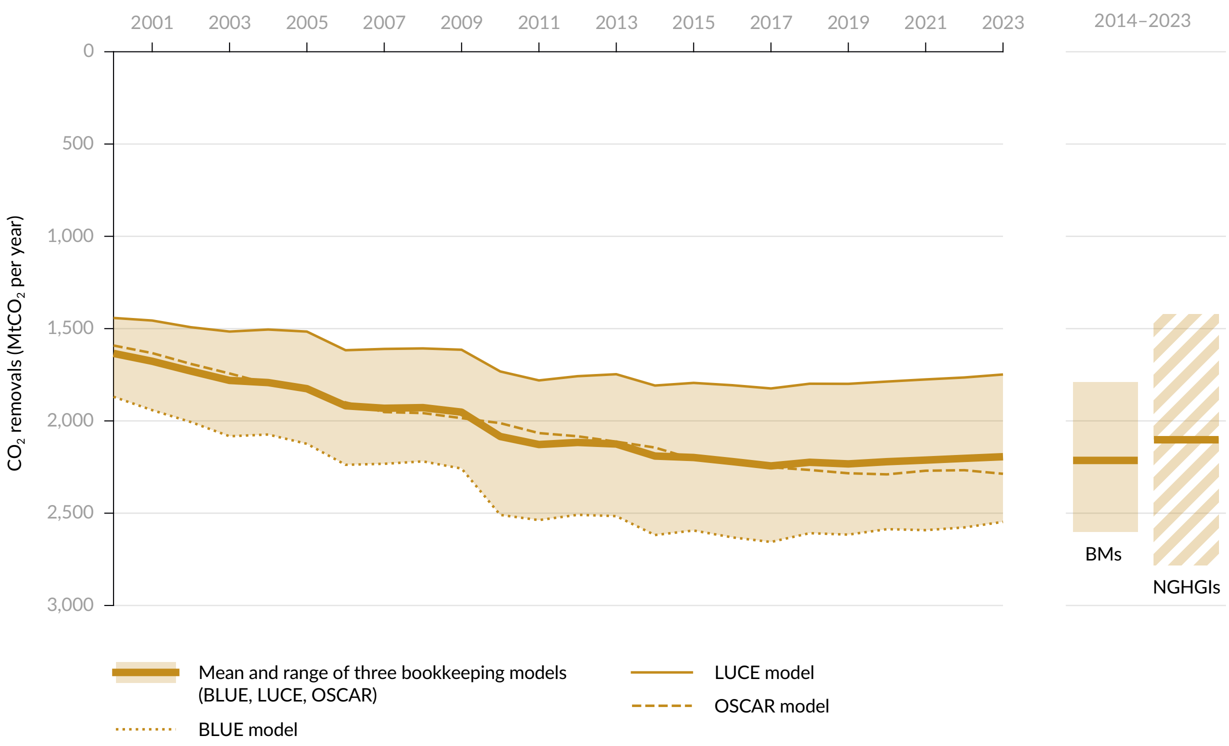
Despite broad alignment in their global estimates of conventional CDR from 2014 to 2023, bookkeeping models and NGHGIs exhibit slightly divergent trends over the longer period from 2000 to 2023: bookkeeping models show a modest increase in CDR whereas adjusted NGHGIs indicate a small decrease (see Figure 7.1a and Figure A7.3 in the Technical Annex).

Bookkeeping models indicate that the highest volume of CDR through afforestation and reforestation at the country level occurs in China, followed by the United States, the European Union, Brazil and the Russian Federation (see Figure 7.1b). Together, these contribute 55% of global CDR from afforestation and reforestation. CDR through afforestation and reforestation is most extensive in East Asia and Europe, with substantial areas in several tropical regions and parts of North America, India and the Russian Federation also providing considerable CDR (see Figure 7.1c). While the global-level estimates generated by the three bookkeeping models are similar, more substantial differences emerge at the country level, particularly for China and the European Union (see Figure 7.1b).

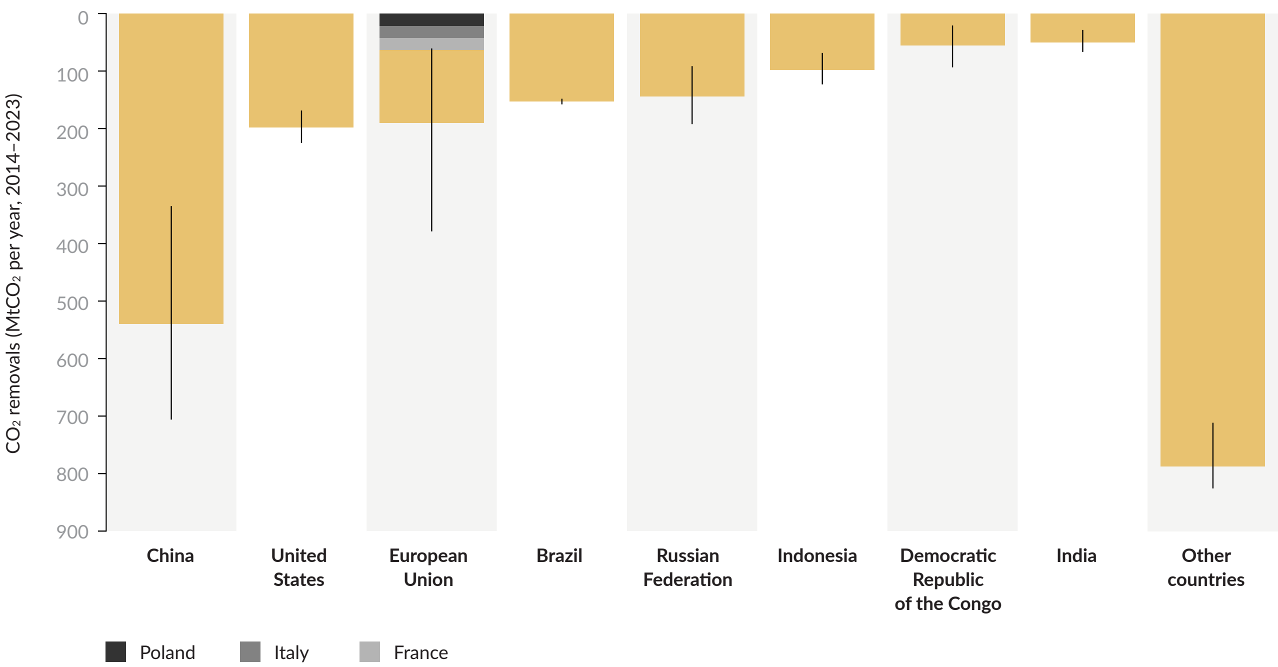
The uncertainties in CDR estimates from bookkeeping models, quantified as differences across model estimates, are substantial (around 20% for 2014 to 2023; see Figure 7.1a). Underlying these uncertainties are land-use datasets (which are partly incomplete and not fully constrained), divergent assumptions regarding carbon stocks in different types of vegetation and soil, and differences in forest growth curves.[11]

CDR rates in forests, by year and region

a) Global CDR through afforestation and reforestation



b) Country-level CDR through afforestation and reforestation



c) CDR through afforestation and reforestation

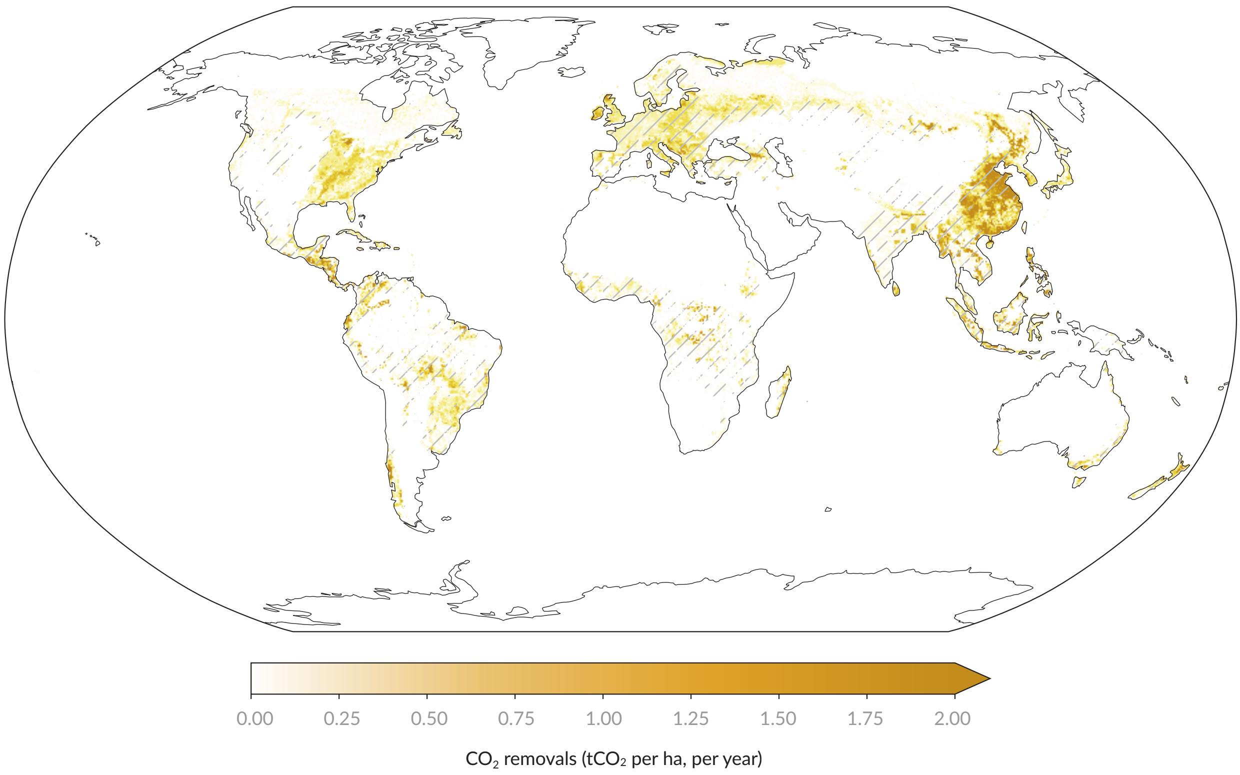


Figure 7.1 *Rates of conventional CDR by year and location. (a) Global estimates of CDR due to afforestation and reforestation, (b) estimates ranked by country and the European Union countries collectively, and (c) global map with CDR estimates. Shading in panel (a) indicates the full range across bookkeeping models and the standard deviation for NGHGIs. Values in panel (b) and panel (c) show averages of the three bookkeeping models from 2014 to 2023. Bars in panel (b) indicate the multi-model mean of the models BLUE, LUCE and OSCAR, and whiskers represent the full spread across their estimates. Country names in the European Union bar indicate the three EU countries with the largest removals from afforestation and reforestation. Grey hatching in panel (c) indicates regions of high inter-model variability (standard deviation > 0.5 × mean; hatching not shown for regions with CDR below 0.01 tCO_2 per ha, per year).*

7.3 Current novel CDR

CDR from novel methods grew from 1.4 $MtCO_2$ in 2023 to 2.0 $MtCO_2$ in 2025. In previous years, this total was dominated by four main methods: biochar, BECCS, enhanced weathering and DACCS. But a slightly different leaderboard emerges in 2024 and 2025.

Biochar remains the largest contributor to CDR, with a significant increase in 2025. Survey results indicate that 0.54 Mt of biochar was produced in 2025. After separating by biomass type and applying decay rates (see the Technical Annex), we estimate biochar removed 1.46 (± 0.16) $MtCO_2$ in 2025, approximately 1.9 times more than in 2023 and nearly three-quarters of total novel CDR in 2025. As our calculations use conservative assumptions, and survey data may be incomplete, this should be considered a lower bound. A comparison of the 2023 and 2025 survey responses suggests that the increase is primarily attributable to real growth in biochar production rather than improved survey coverage (see the Technical Annex).

BECCS remains the second-largest contributor. In 2025, BECCS removals totalled 0.51 $MtCO_2$, a slight decrease from 0.61 $MtCO_2$ in 2023. Three facilities were operational in 2025, all in the United States: Blue Flint Ethanol, which commenced operations in 2024; Gevo (formally Red Trail Energy); and the ADM bioethanol CCS facility in Decatur, Illinois. The Illinois facility temporarily paused injections in October 2024, following detection of fluid migration in the storage reservoir, and resumed operations in September 2025. In the absence of a complete estimate, we assume capture for the Illinois facility at its typical annual removal rate (0.43 $MtCO_2$),[9] scaled to account for the months of operation for both 2024 and 2025. This approach assumes a constant capture rate throughout the year; in practice, capture rates may fluctuate due to operational ramp-up following a pause, maintenance or other downtime. Consequently, the estimate presented here should be interpreted as an approximation, rather than a precise annual total. The apparent decrease in total BECCS removals in 2025 is primarily due to this injection pause; if the Illinois facility had been operating throughout, combined BECCS CDR would have reached 0.8 $MtCO_2$.

Biomass burial became the third-highest contributing CDR pathway in 2025, removing 0.05 $MtCO_2$, a 21-fold increase relative to 2023, but still minor compared to biochar or BECCS. This increase was driven mainly by two US companies – Vaulted Deep and Graphyte – with additional activity from companies in Australia and Namibia. Bio-oil storage was the fourth-largest contributor in 2025, with 0.006 $MtCO_2$, led by Charm Industrial and NULIFE GreenTech.

In 2025, enhanced weathering removals totalled 0.0038 $MtCO_2$, lower than the 0.03 $MtCO_2$ reported for 2023 in *The State of CDR 2nd Edition*. But this drop needs context, as it reflects a revised methodology that includes only values explicitly verifiable via public documentation (see the Technical Annex). Further, these figures represent actual quantified CDR based on in-field measurements and modelling, rather than the full potential of deployed rock. While these values suggest a decline, enhanced weathering activity expanded substantially in 2024 and 2025, with companies such as Mati Carbon and Terradot spreading approximately 50,000 tonnes of basalt across multiple regions in India and approximately 48,000 tonnes over 1,800 ha in Brazil. Because CO_2 removal occurs progressively as silicate weathering proceeds, there is an inherent time lag between rock application and CO_2 uptake, meaning that the remaining deployed rock will continue to generate additional removals in subsequent years. Estimates for both 2024 and 2025 may be conservative; the joint survey with CDR.fyi identified additional enhanced weathering activity associated with a Columbian consortium operating in the coffee sector, which reports removals but does not yet have public documentation of issued credits. Inclusion of this project would raise estimated enhanced weathering CDR to 0.013 $MtCO_2$ in 2024 and 0.014 $MtCO_2$ in 2025.

CDR in mineral products contributed 0.0022 $MtCO_2$ in 2025, primarily through CO_2-cured concrete. Much of this activity came from O.C.O Technology, a UK-based company. Notably, 11% of the CO_2 removal credited via registries to this project originated from biomass used in waste-to-energy facilities, while the remainder was captured from ambient air during curing. We do not include the latter in our estimates (see Section 7.1).

In 2025, DACCS removed 0.0015 $MtCO_2$. This appears lower than the 0.004 $MtCO_2$ reported for 2023 in *The State of CDR 2nd Edition*; however, CDR from DACCS has in fact increased 18-fold over this period. The 2nd Edition value was an estimate based on the full operational capacity of the Climeworks Orca facility, which was the only operating DACCS plant at the time.[9] Available registry data now indicates that Orca captured substantially less CO_2 in 2023 than its full capacity, requiring a downward revision of our historical DACCS estimates.

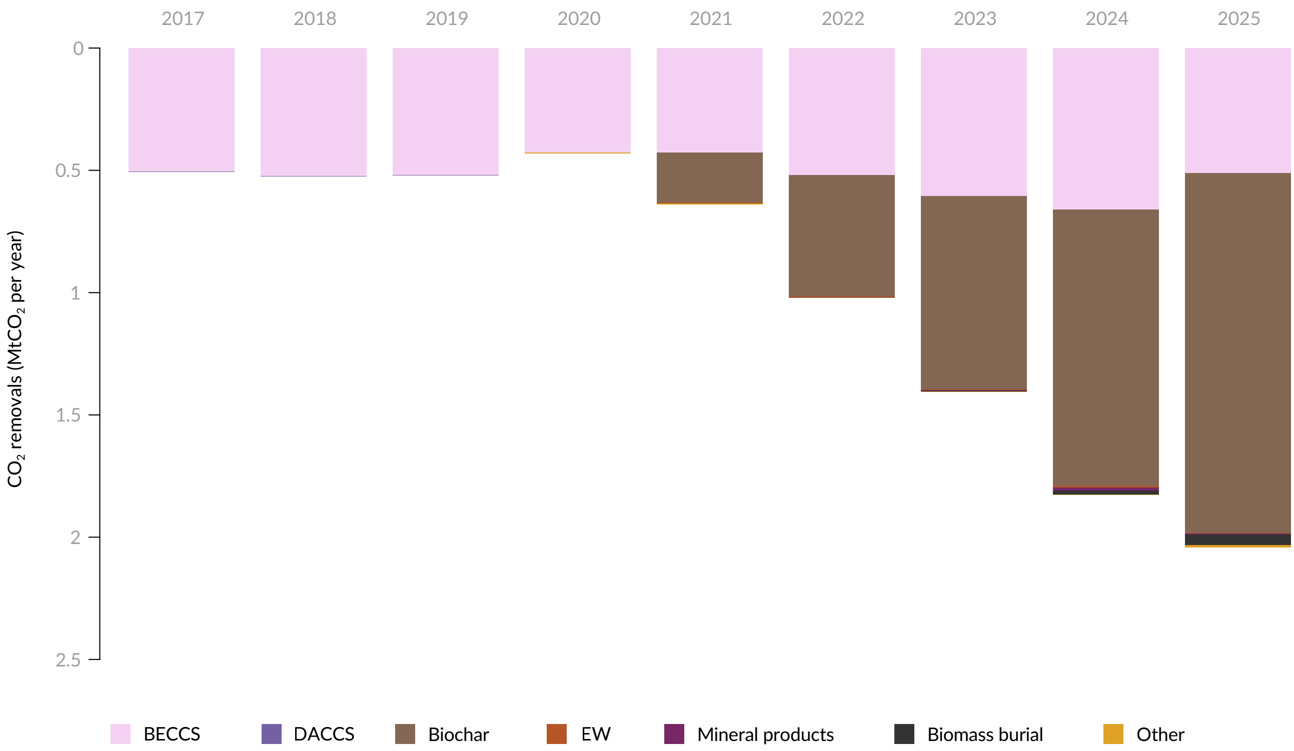
Updated values in this 3rd Edition reflect actual CO_2 capture from Orca and also from Climework's newer facility, Mammoth, which came online in 2024. Both are still operating below full capacity in 2025; however, both facilities have increased their annual removal rates from 2024 to 2025.

Values for these facilities are based on data available up to October 2025; updated registry data for the final two months in 2025 may slightly increase these totals. Company announcements also indicate that Heirloom's joint project with CarbonCure (Tracy DAC Hub; 0.001 $MtCO_2$ per year capacity[9]) is active, but as this cannot be verified via other sources (e.g. CDR.fyi) it is not included. Project Hummingbird and Deep Sky Alpha commenced in 2025, but Isometric has yet to verify any removals.

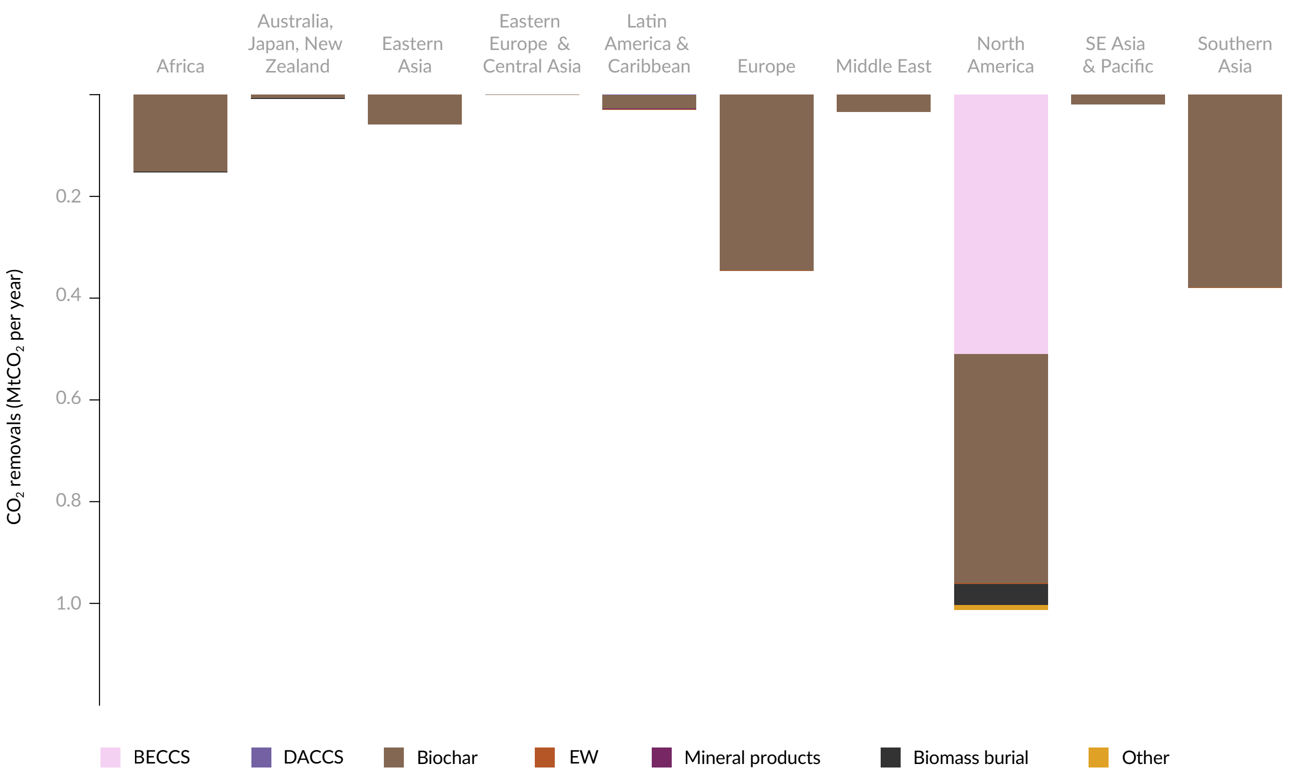
Finally, other methods, such as alkalinity enhancement of water bodies and DOCCS are also active but at smaller scale, removing a combined 0.004 $MtCO_2$ in 2025.

Novel CDR rates, by year and region

a) Novel CDR globally, 2017–2025



b) Novel CDR by region in 2025



c) Novel CDR by location in 2025

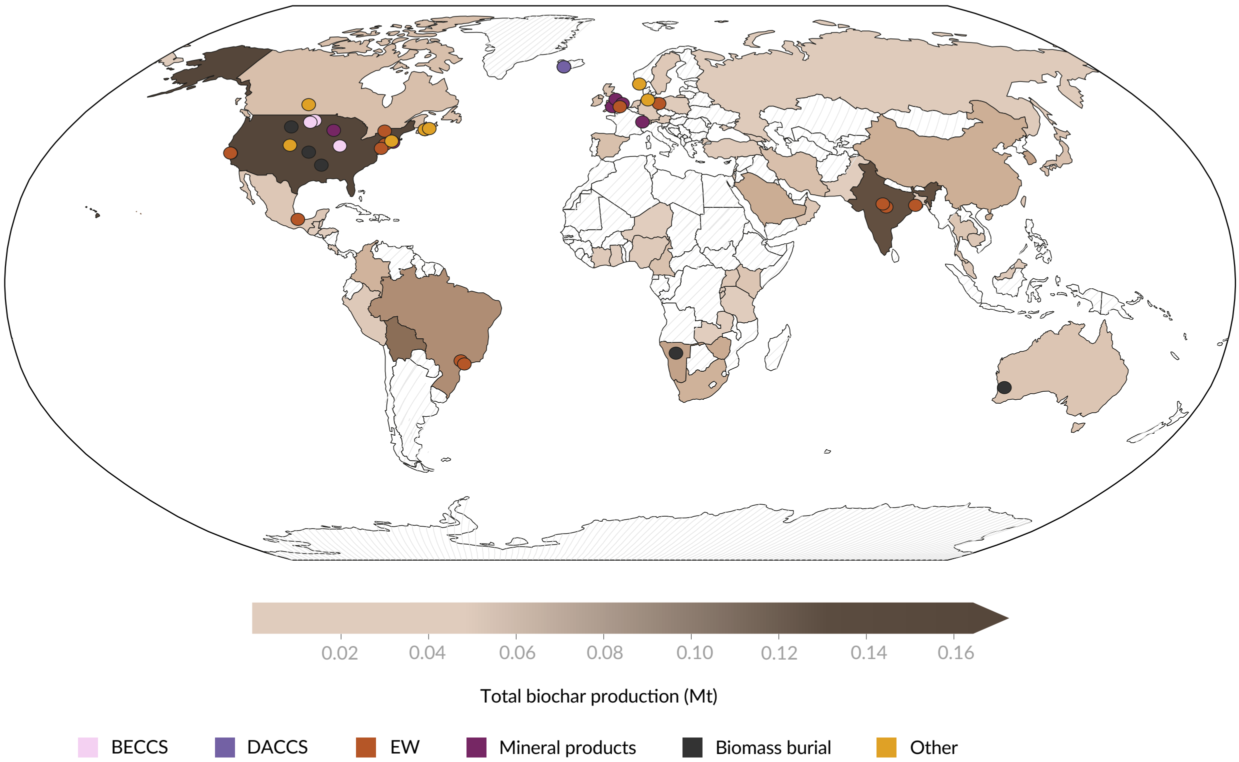


Figure 7.2 *Rates of novel CDR rates by year and location. (a) Global time series during 2017–2025, (b) region-specific global CDR in 2025, and (c) global map depicting biochar produced in 2025 by location, with operational sites for other novel pathways also shown (represented by coloured dots) The 2024 BECCS total includes approximately 0.32 $MtCO_2$ from the ADM bioethanol CCS facility before injection paused in October 2024; the 2025 total includes approximately 0.14 $MtCO_2$ from the facility after it resumed operations in September 2025.*

As noted in Section 7.1, the above estimates represent the gross amount of CO_2 moved from the atmosphere to durable storage, minus any subsequent re-release. This differs from the CO_2 removal reported in carbon credit registries for these projects, as registries tend to report net CDR after including emissions from the wider project lifecycle. When using registry data for our estimates, we have extracted the gross component only, but the net values available from these registries and other lifecycle estimates are also informative (see Box 7.1).

Box 7.1 The implication of assessing gross versus net removals for novel CDR: a lifecycle approach

LCAs for current CDR projects are available from carbon registries and scientific studies. LCA results, in general, vary widely, as studies apply different boundary conditions and methodologies.[12] There is currently no consistent approach to such assessments for CDR methods, making comparisons difficult.[13] Nevertheless, studies report that net CDR is typically much lower than the gross total CO_2 captured from the atmosphere. Here, we briefly summarize what is usually included (or excluded) in available project LCAs, and what they imply for four of the primary project types currently delivering novel CDR.

BECCS with bioethanol: In bioethanol-based BECCS projects, CO_2 is captured during ethanol production from biomass. Two distinct LCA boundary choices may be applied. When a CO_2 capture unit is retrofitted onto an existing bioethanol plant, the counterfactual baseline for LCA assumes ethanol production would have occurred anyway. This means emissions are counted from CO_2 capture, compression, processing and injection.[14] With this system boundary, net removal may be only 2%–13% below gross CO_2 captured (represented as the upper end of the range in Table 7.1). By contrast, whole-system LCAs draw boundaries around the wider bioethanol system – including direct and indirect land-use change, biomass cultivation, harvesting and bioethanol production. This broader boundary substantially reduces net CO_2 removal. In some cases, bioethanol facilities with CCS may become net emitters to the atmosphere (the value of -68% in Table 7.1 indicates that for every 1 tCO_2 captured, 1.68 tCO_2 is emitted). Replacing fossil fuels in bioethanol production with low-carbon energy would significantly improve net removal.[15]

DACCS: LCA boundaries for DACCS facilities generally include equipment manufacture, emissions during capture and processing of the CO_2 and transport into geological storage.[14] The net carbon balance is strongly dependent on the carbon intensity of the energy supply.[16] While many DACCS projects are currently under various stages of planning, only two have traceable online LCA documentation at the time of writing: Orca and Mammoth. These facilities have relatively low emissions associated with their energy supply because they are powered by a nearby geothermal source. Nevertheless, even with renewable energy, reported LCA emissions have varied substantially, reducing net removals to 23%–90% of gross values (see Table 7.1).[17,18]

Biochar: Biochar is produced from a range of biomass feedstocks, many of which are waste or residue streams from other production systems (e.g. wood waste, agricultural residues and manure). Where waste biomass is used, avoided emissions from the baseline scenario where it would otherwise decay or be combusted are not credited. Emissions associated with land-use change or biomass cultivation are usually allocated to the co-product rather than to biochar,[19] although these emissions are included where biomass is cultivated specifically for biochar production. Emissions from feedstock transport and pyrolysis are always included. Although biochar application can influence soil carbon dynamics – such as by enhancing plant CO_2 uptake or increasing soil organic carbon[20] – any additional carbon accumulation beyond the biochar is not credited. Biochar decay is also accounted for, with registry protocols applying durability adjustments over 100 years (i.e. puro.earth)[19] or 200 years (i.e. Isometric)[21] following methods derived from Woolf et al. (2021). Overall, net removals are approximately 60%–92% of gross CO_2 captured in biochar (see Table 7.1), with the range due to differences in decay accounting and inclusion of biomass growth and harvesting in LCA emissions.

Enhanced weathering: Emissions from mining, grinding, transport, spreading and monitoring are typically included in enhanced weathering LCAs. Emissions can vary widely between projects, depending on whether waste fines are used or fresh rock is mined, as well as the transport distance. Consequently, deductions from gross CDR can vary considerably between individual projects. Across current enhanced weathering projects listed on registries, deductions from gross CDR to reflect LCA emissions average 6% but range from 5% to as much as 43%. In addition, LCAs apply further, often conservative, deductions to account for uncertainty in carbon losses during transport between application sites and long-term storage in the ocean. These adjustments, which can oversimplify site-specific processes and remain conservative pending improved coupled ocean-atmosphere modelling, lead to an average reduction in removals to 68% of gross CO_2 captured (gross CO_2 stored durably, see Table 7.1). The overall net removal range reported in Table 7.1 (28%–79% of CO_2 captured) is derived directly from project-level registry data, in which both LCA emissions and potential CO_2 re-release are incorporated, rather than being calculated from the average deduction values presented above.

Gross CDR reductions due to CO_2 losses and emissions

	Gross removal		LCA emissions					Net removal range
CDR method	Gross CO_2 captured	Gross CO_2 stored durably	LUC/ iLUC	Feedstock sourcing	Feedstock processing	Capture/ transport	Burial/ injection/ monitoring	Net CO_2 removed
BECCS	100%	100%	✗	✗	✗	✓	✓	-68%–98%
DACCS	100%	99% (99%–100%)	n/a	n/a	n/a	✓	✓	23%–90%
Biochar	100%	92%–99%	✗	M	✓	✓	✓	60%–92%
EW	100%	71% (44%–85%)	n/a	M	M	✓	✓	28%–79%

Table 7.1 *Note: Gross CDR reductions due to CO_2 losses and emissions. Percentage reductions are based on data compiled from registries and peer-reviewed LCA studies.[15,22,23] After initial atmospheric CO_2 removal (gross CO_2 captured), losses from downstream processes reduce this value (gross CO_2 stored durably). The LCA emissions panel shows typical cradle-to-grave emissions components across the full system boundaries. For each method, LCA components are marked either with a tick (included), cross (excluded) or M (sometimes included) based on current registries. The net CO_2 stored illustrates how LCA coverage impacts overall reductions, with the range reflecting varying LCA boundaries. LUC refers to direct land-use change, and iLUC represents indirect land-use change. The negative value for BECCS (-68%) is estimated by Dees et al. (2023)[15] and indicates net emissions for a bioethanol facility when considering the whole system, including co-products.*

7.4 Carbon transfers between durable stores

The transfer of carbon between durable stores can represent part of a CDR activity, though it does not generally reflect withdrawal from the atmosphere in that same year. The transfer of carbon to durable harvested wood products amounts to 780 $MtCO_2$ per year averaged over the period 2014 to 2023. The net flux of durable harvested wood products, considering also the re-release of CO_2 through their decay, amounts to 330 $MtCO_2$ per year averaged over the period 2014 to 2023 (see Figure 7.3).

The total CDR from biochar represented in Figure 7.2 includes CDR via all feedstocks used to produce biochar. Of the total CDR from biochar in 2025 (1.46 $MtCO_2$), 67% came from woody biomass, representing 0.97 (woody biomass transfer post decay) $MtCO_2$ of net carbon transfer between durable stores in addition to sawnwood and panels (see Figure 7.3).

To avoid overestimating total CDR, these carbon transfers relating to CDR should not be added directly to the above removals from afforestation and reforestation estimated by bookkeeping models. This is because the carbon transfers into harvested wood products may originate from long-managed forests, or from recently afforested or reforested areas. In the former case, the contribution is additional to CDR from afforestation and reforestation estimated by bookkeeping models. In the latter case, part of the carbon removal associated with harvested wood products may already be accounted for by bookkeeping models during forest growth in afforested and reforested areas, potentially resulting in double counting.

CDR transfers between durable stores

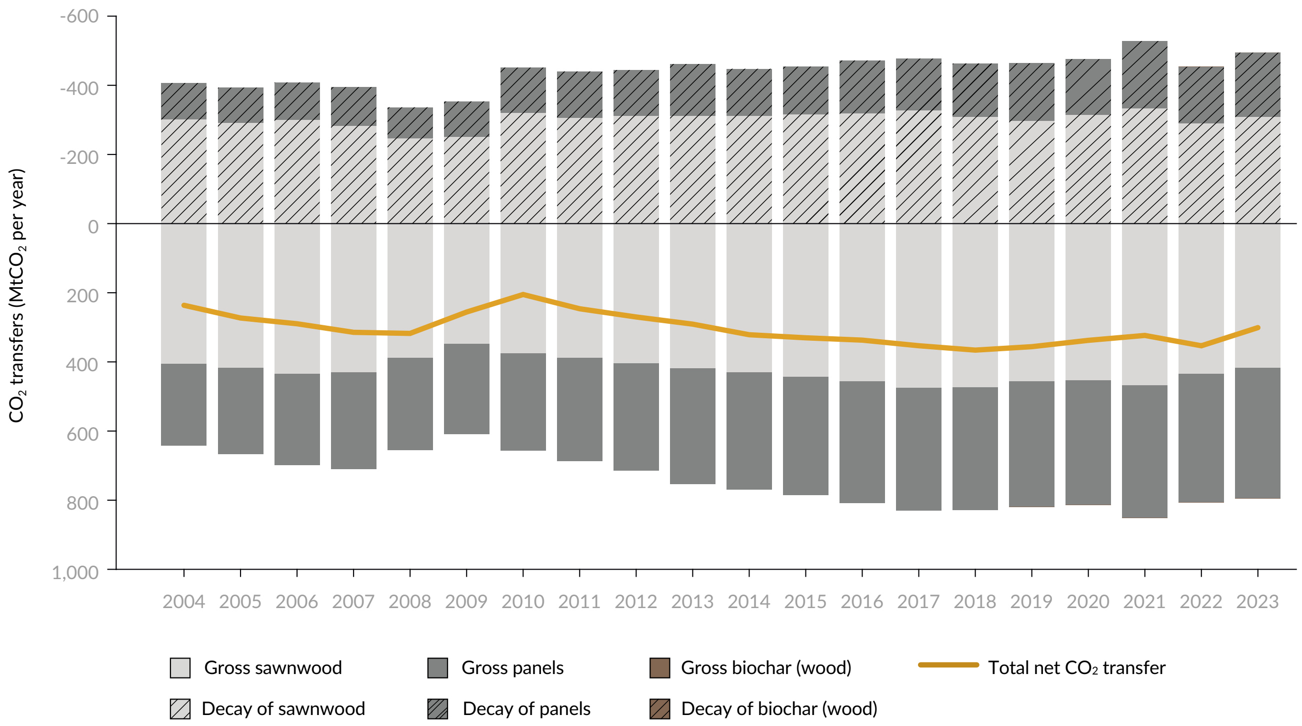


Figure 7.3 *Annual time series of net CO_2 transfer from biomass to durable storage (sawnwood, panels and biochar), accounting for re-release through decay, with methods detailed in the Technical Annex. Total net CO_2 transfer is the total net transfer from sawnwood, panels and biochar combined (gross – decay). Note that biochar fluxes in and out are much smaller than hardwood products and thus hardly visible in the figure. Sawnwood refers to wood cut directly from logs into products such as planks, beams or boards (>6 mm thick), while wood-based panels are manufactured products made from wood fibres, particles or veneer sheets, such as plywood and fibreboard.*

7.5 CDR deployment pipeline

Conventional CDR is expected to remain the dominant form of carbon removal in the near term, but forecasts of CDR from afforestation, reforestation and land management activities are not generally available. Near-term demand will be driven by a range of factors including policy goals and land-use pledges (see Chapter 8) alongside a small contribution from the VCM (less than 1% of current removals; see Chapter 4). However, broad government commitments do not necessarily translate directly into defined projects under active development.

For novel CDR, company ambitions total approximately 42 $MtCO_2$ per year of removals by 2030 (see Chapter 3). However, many of these ambitions do not necessarily provide concrete details of upcoming projects and are thus speculative and subject to change.

A more grounded estimate of the near-term pipeline for novel CDR is obtained by assessing projects currently under construction alongside the operations of existing projects. Estimates of the capacities of DACCS and BECCS facilities under construction are available from the IEA.[9] Based on these estimates, projected CDR reaches 0.55 $MtCO_2$ per year from DACCS and 4.8 $MtCO_2$ per year from BECCS by 2030 (see Figure 7.4). These values assume that these facilities achieve their estimated capacities and are not subject to permitting, financing and MRV bottlenecks.

Our biochar estimates draw on short-term CDR targets in documentation from operating projects, currently only publicly accessible for companies listed on Isometric. The projected additional 1.5 $MtCO_2$ per year by 2030 should therefore be considered conservative, particularly as survey data indicate that commercial and non-commercial pipeline ambitions may exceed 3 $MtCO_2$ per year by 2030.

Furthermore, rock spread through enhanced weathering projects is expected to continue providing CDR in the years ahead; based on data compiled from publicly available documentation, this could contribute an additional 0.1 $MtCO_2$ of removals. Taken together, these projections suggest novel CDR capacity could increase to approximately 8.4 $MtCO_2$ per year by 2030.

Estimated annual pipeline of novel CDR capacity, 2023–2030+

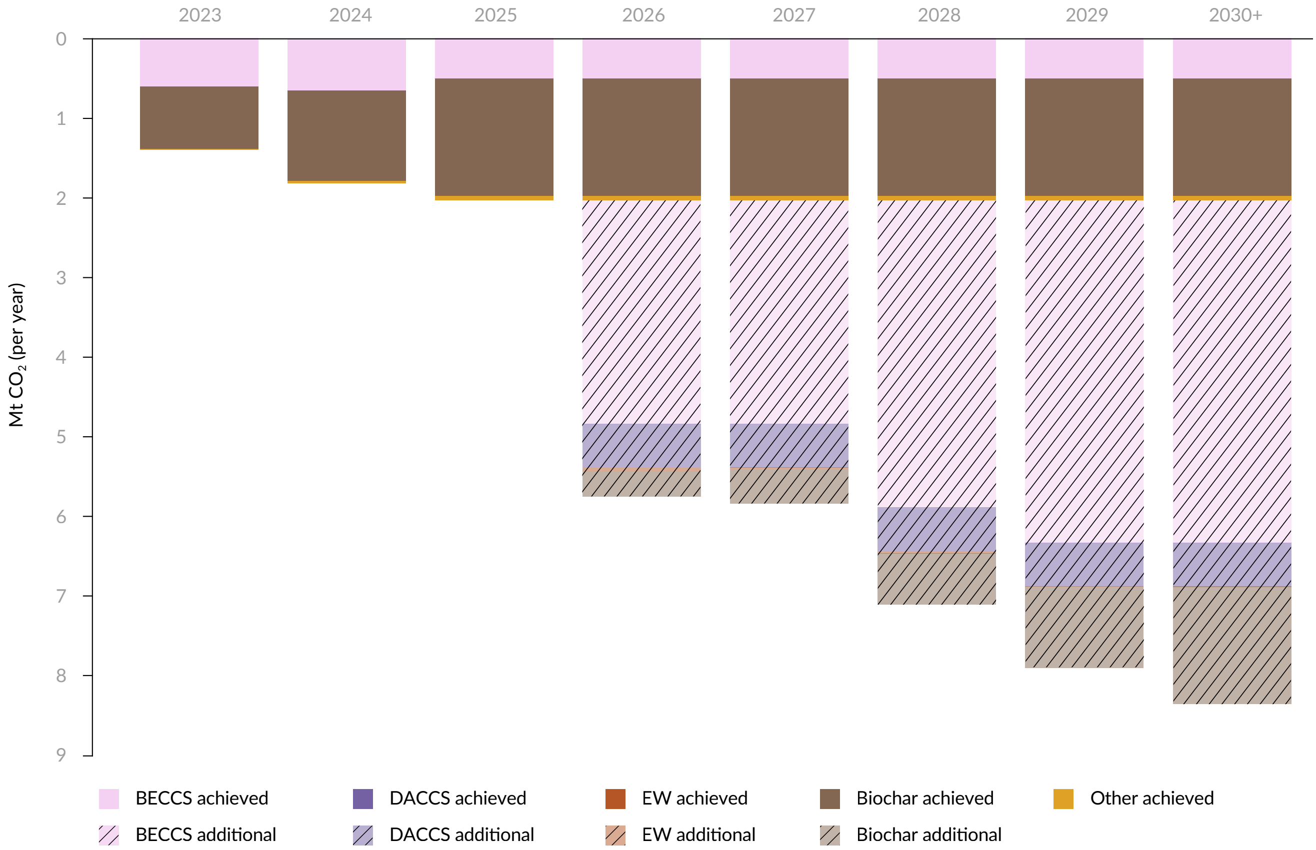


Figure 7.4 *Solid bars show achieved novel CDR for 2023–2025 and 2025 levels carried forward for 2026–2030. Faded patterned bars indicate additional capacity from new or scaling projects for 2026–2030. Note that for EW and DACCS, actual CDR is much smaller than BECCS and biochar so is hardly visible here. For BECCS, DACCS and biochar, the CDR capacity from new facilities under construction is included. For EW, values include only rock spread that has yet to deliver CDR.*

Comparing 2025 deployment with previous projections

The State of CDR 1st Edition, drawing on company announcements about planned facilities, projected that novel CDR deployment could increase eleven-fold from 1.0 $MtCO_2$ per year in 2022 to over 11 $MtCO_2$ per year by 2025. However, actual deployment in 2025 merely doubled to 2.0 $MtCO_2$. A major reason for this more modest expansion was the hold placed on the Summit Carbon Solutions BECCS project in the United States, which had intended to capture CO_2 from 30 Midwestern bioethanol plants and transport it via pipeline to North Dakota for permanent storage. In 2025, however, pipeline construction was suspended until 2028 due to local opposition.

The difference between what was projected and what actually occurred highlights the challenge of forecasting growth in novel CDR. Projects often face schedule delays, operational issues and financial, regulatory or technical constraints; these may produce knock-on effects that diminish operational capacity and delay or prompt the cancellation of the project. Consequently, not all capacity from the pipeline projects shown in Figure 7.4 may materialize.

Box 7.2 Limitations and knowledge gaps

Several improvements in our analysis of CDR capacity have been made since *The State of CDR 2nd Edition*, including updates to data sources, methodological refinements and expanded coverage of both conventional and novel CDR approaches. Nonetheless, some gaps and limitations remain. These are covered in the Technical Annex and summarized here.

- Distinguishing CDR from natural fluxes: Clearly delineating the effects of direct human activity on land from the indirect effects resulting from a changing environment is challenging, as observations alone are insufficient. Bookkeeping models have an internally coherent framework for this separation, but uncertainty is present from differing assumptions across the models, simplifications of complex land processes and poorly constrained input parameters. The estimates of CDR from NGHGIs are even more uncertain, as they rely on the subtraction of indirect effects in managed forests using dynamic global vegetation models.

- Improving the comparability of CDR estimates from bookkeeping models and NGHGIs: Bookkeeping models estimate CDR from afforestation and reforestation. By contrast, many NGHGIs report “land converted to forest” (which contains CO_2 fluxes in the first 20 years after land conversion) as well as fluxes from management of other, pre-existing forest land. It may be possible to improve comparability by extracting equivalent fluxes from bookkeeping models, which are currently not available.

- Accounting for re-release of CO_2 in forests: Bookkeeping models do not account for disturbance events. This means that their CDR estimates for afforestation and reforestation exclude changes in durability due to wildfires, droughts and similar effects. This may lead to an overestimation of conventional CDR, particularly under continued warming, and has implications for the long-term reliability of conventional CDR. The estimate of CDR in managed forests based on NGHGIs does capture such changes to some extent.

- Reconciling forest-based commitments with realized carbon removals: Estimates of near-term deployment of conventional CDR to meet forest-based restoration pledges and forward crediting commitments are constrained by limited information on the timing, location and extent of implementation. Commitments are typically reported as aggregate land-area targets or anticipated credit volumes, without systematic linkage to observed land-use change or national inventory reporting, making it difficult to assess whether pledged areas are already included in existing estimates. Although bookkeeping models can quantify removals where activities are implemented and reported, uncertainties related to implementation, additionality, durability and potential overlap across policy pledges, national inventories and voluntary carbon market claims limit the reliability of forecasts of realized removals resulting from such commitments.

- Computing downstream CO_2 loss via enhanced weathering and alkalinity enhancement: These novel methods have advanced rapidly in recent years, prompting community efforts to develop accounting protocols. For example, many enhanced weathering projects apply a uniform 20% reduction to gross CDR to account for re-equilibration of weathering products with ocean waters, plus further reductions for additional loss processes such as carbonate precipitation. While intentionally conservative, these loss allowances remain highly uncertain.

- Accounting for the re-release of CO_2 from biochar: Our estimates of CDR from biochar now include CO_2 re-released through decay. These estimates are strongly influenced by soil temperature, which varies in space and time, but only country-level data is available for biochar applications. We therefore use national average annual soil temperatures to calculate decay. While we adopt conservative assumptions and estimate the uncertainty arising from variations in soil temperature, more spatially explicit data would enable refinement for future editions.

- Highlighting gaps in tracking CDR activities: Not all current activities that may lead to CDR are tracked in this chapter. Among the likely largest missing contributors are peatland and coastal wetland restoration, and soil carbon sequestration in croplands and grasslands. Activity data for biochar (and some other projects) relies on survey responses. Such surveys are unlikely to capture all projects, particularly those by smaller producers, meaning that total activity is likely underestimated.

7.6 Outlook

CDR is being deployed with different methods in a wide variety of locations around the world (see Figure 7.5). By far the most widely deployed method is afforestation and reforestation, with removals totalling around 2,200 $MtCO_2$ per year on average over the last decade. A significant amount of woody biomass is transferred from forests into durable products, although their gradual decay leads to substantial CO_2 re-release as well. Novel CDR methods delivered removals of around 2.0 $MtCO_2$ globally in 2025, led by biochar and followed by BECCS, biomass burial and mineral products. Of this, 0.51 $MtCO_2$ is stored in geological formations and minerals, the most durable forms of storage. While these amounts are far smaller than conventional CDR rates, novel CDR has been growing at a faster rate – around 36% from 2020 to 2025.

Some significant limitations and knowledge gaps hamper our ability to track CDR developments, leading to uncertainties in our estimates (see Box 7.2). Improvements in methodology, as well as changes in real-world activity, may push future estimates lower or higher.

Current levels of CDR deployment are much lower than current gross CO_2 emissions, which amount to about 44,000 $MtCO_2$ per year.[2] The current CDR rates are also lower than the future levels of CDR required even in pathways that reduce emissions deeply to meet climate goals (see Chapter 8). While this chapter finds a number of CDR projects in active development, which should lead to a further increase in capacity, recent history shows that delivery tends to be lower and slower than such capacity projections indicate.

Summary of current atmospheric fluxes and transfers from CDR activities

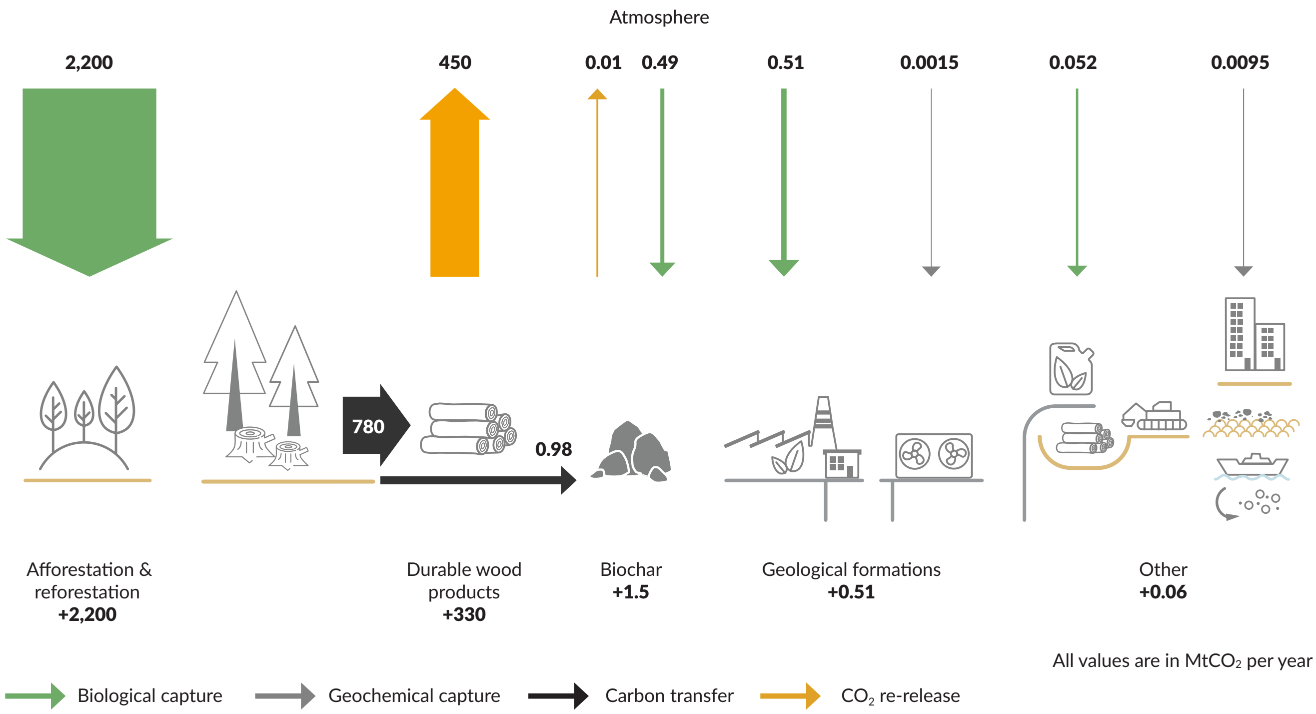


Figure 7.5 *Summary of current atmospheric CO_2 fluxes and transfers from CDR activities based on average conventional CDR levels between 2014 and 2023, and estimated novel CDR in 2025. Downward arrows indicate fluxes out of the atmosphere due to CDR activity, while upwards arrows indicate fluxes back into the atmosphere from storage. Conversion of woody biomass is indicated as a carbon transfer (horizontal arrows); transferred carbon is typically captured from the atmosphere in previous years. Durable carbon stores are labelled at the bottom, along with net changes in CO_2 stored (bold numbers). All numbers shown to two significant figures.*

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Chapter 8

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Biogas plant in rural area with rapeseed field. By Ralf Geithe

Chapter 8 | Paris-consistent CDR scenarios

Scenarios that explore climate change mitigation futures have increasingly diversified the CDR methods they model. All scenarios we assess as consistent with the Paris Agreement grow both novel and conventional CDR by a gigatonne or more in 2050 to limit the amount and duration of 1.5°C overshoot. But the balance between novel and conventional CDR methods depends on the speed of emissions reductions as well as limits to sustainable land and biomass use.

Key insights

- Scenarios have expanded the representation of CDR methods from afforestation, reforestation, BECCS and DACCS to include enhanced weathering, ocean-based methods, biochar, long-lived materials and other methods.
- New scenario evidence modelling the highest possible ambition pursued with immediate action exhibits CDR levels of 3.9 (full range 2.7–4.1) $GtCO_2$ deployed by 2035 and 8.8 (full range 6.5–13.3) $GtCO_2$ by 2050. CDR accounts for around 16% of mitigation effort cumulatively when net-zero CO_2 is achieved, compared to 84% due to reducing sources of emissions. Temperatures peak in these scenarios between 1.7°C and 1.8 °C.
- Scenarios pursuing delayed ambition for ten years compared to immediate action show temperature peaking around 0.15°C higher than with highest ambition. They tend to have lower near-term CDR deployment through 2050, but then require higher CDR deployment after mid-century to return warming to 1.5°C.
- CDR is deployed at scale even in scenarios modelling current climate targets and pledges, primarily through expanded use of conventional CDR on land and with novel CDR reaching gigatonne levels by 2050.
- Scenarios modelled by national research teams show a variety of deployment patterns and highlight the need for both global and national analyses to understand sustainable CDR pathways.
- Early and sustained emissions reduction actions ease CDR scaling and feasibility concerns, whereas delay creates higher future reliance on CDR and stronger climate impacts. Increasing required volumes of CDR intensifies social and economic constraints and raises sustainability concerns related to land, water, ecosystems and resource demands associated with such deployment. Implementation-specific details dictate the ultimate co-benefits or negative impacts of CDR projects, which are only partially represented in large-scale scenarios.

Achieving the Paris Agreement temperature goal requires quickly reducing current sources of fossil fuel and deforestation emissions and further addressing residual CO_2 and non-CO_2 emissions from hard-to-transition sectors, including agriculture, heavy industry, aviation and shipping. CDR methods have emerged as a critical complement to emissions reductions in long-term pathways, as highlighted in the Working Group III Contribution Report to the Sixth Assessment Report from the IPCC. Specifically, CDR can balance remaining sources of emissions to achieve net-zero and then enable net-negative CO_2, stabilizing temperatures and potentially reversing overshoot. In this chapter, we evaluate scenarios targeting multiple aspects of the Paris Agreement, examining the scale, timing and sustainability implications of different CDR scenarios. We use scenario evidence developed by integrated assessment model (IAM) teams to understand how these goals can be achieved while also accounting for feasibility and sustainability limits (see Box 8.1).

Scenario evidence can be assessed in different ways. For example, IPCC reports normally study unstructured ensembles of scenarios from existing scenario databases.[1] We followed this approach in *The State of CDR 1st Edition*, where we analysed CDR outcomes from the IPCC's Sixth Assessment Report (AR6) scenario database[2] which meet the temperature goal of the Paris Agreement. In the 2nd Edition, we compiled additional scenarios published since AR6 and applied ex-post analysis based on wider sustainability considerations to understand which scenarios achieve the temperature goal in more sustainable ways. While these assessments continue to be useful, they also depend on ever-outdated scenario evidence where emissions reductions and ambitious action begin in what is now the past (e.g. in 2020). Given that actual global emissions have not followed these trajectories, such scenarios now underestimate the scale and reach of both emissions reductions and CDR deployment needs. They further lack updated technoeconomic assumptions of mitigation technologies and represent a relatively limited set of CDR methods.

In this 3rd Edition, we go further: we worked directly with modelling teams to develop a targeted multi-model comparison using a consistent scenario protocol (see Technical Annex 8.1). The protocol defined three scenarios.

1. Mitigation effort consistent with current climate targets[i] and pledges (excluding the United States) submitted to the UNFCCC under the Paris Agreement (*Targets & Pledges*);

2. Mitigation effort consistent with highest possible ambition (*Highest Ambition*); and

3. Mitigation effort shifting from current targets and pledges to highest possible ambition after ten years of delay (*Delayed Ambition*).

[i] Current targets include both national determined contributions (NDC) and long-term low greenhouse gas emissions development strategies (LT-LEDS), frequently called "net-zero targets".

We asked teams to develop these scenarios using explicit considerations of sustainability (e.g. protecting biodiverse and high-carbon ecosystems, safeguarding food security and increasing energy efficiency), and we assess scenarios consistent with near-term feasibility boundaries in the scientific literature (e.g. scale-up rates of novel technologies, including related technologies like CCS[3]). The protocol generally avoids mandating specific levels or values in terms of these constraints, instead focusing on understanding the modelling teams' interpretation of such goals to foster a richer and common comparison for analysis. To enable a consistent comparison between scenario CDR estimates and current deployments, we harmonize present-day levels of CDR in scenarios with those assessed in Chapter 7.

These scenarios present a new and evolving evidence base for assessing levels of CDR needed to meet the Paris Agreement temperature goal. The results we present are based on new research and the latest model versions focused on CDR implementation[ii] which we expect to be updated and refined as teams continue to improve their modelling frameworks and the representations of the scenarios assessed here. Compared to previous assessments, the number of scenarios included in this 3rd Edition is smaller. However, the adoption of a common protocol substantially improves the robustness and comparability of results across modelling frameworks. Eight global modelling teams provided scenarios for assessment, and five national modelling teams provided scenarios consistent with the protocol. Because teams used their latest model versions, the number of CDR methods represented has substantially increased over past assessments (see Table 8.1), allowing for a more comprehensive exploration of mitigation portfolios and their associated trade-offs.

Coverage of CDR methods and number of scenarios across SoCDR editions

Scenario category	Number of scenarios	Afforestation, reforestation, forest management	BECCS	DACCS	EW	Biochar soil amendment	Ocean-based methods	Long-lived materials
SoCDR 1st Edition	540 (100%)	530 (98%)	516 (96%)	146 (27%)	4 (1%)	1 (0%)	0 (0%)	0 (0%)
SoCDR 2nd Edition	630 (100%)	620 (98%)	601 (95%)	217 (34%)	15 (2%)	1 (0%)	0 (0%)	0 (0%)
SoCDR 3rd Edition Global Models	24 (100%)	24 (100%)	24 (100%)	23 (96%)	20 (83%)	12 (50%)	6 (25%)	12 (50%)

Table 8.1 *Note: For the 3rd Edition, modelling teams have reported which methods their models represent, but not all represented methods may be used in all scenarios. For methods in previous editions, we relied on reported variables (see TTechnical Annex 8.2). Ocean-based methods include ocean fertilization, DOCCS and alkalinity enhancement of water bodies. Long-lived materials include harvested wood products and bioplastics.*

[ii] Global teams include: AIM[4], IMAGE[5], GCAM[6], MESSAGEix-GLOBIOM[7,8], OPEN-PROM[9], POLES[10], REMIND-MAgPIE[11,12], and WITCH[13]. National teams include: GCAM-China[14,15], GCAM-Europe[16], GCAM-India[17], GCAM-KSA[18], and GCAM-USA.[19]

Building on this expanded scenario evidence, this chapter examines the role of CDR in long-term mitigation scenarios aligned with the Paris Agreement temperature goal, focusing on: (1) the scale and timing of CDR deployment under different temperature targets and net-zero timeframes; (2) representation of sustainability constraints, including land, water, biodiversity and social impacts; and (3) the underlying assumptions and uncertainties that drive the projected reliance on CDR. This analysis presents temperature and CDR pathways; explores modelling approaches and trade-offs; provides country-level CDR profiles; and discusses risks, unintended consequences and lessons for sustainable deployment.

Box 8.1 IAM scenario evidence

IAMs are simplified representations of complex physical and social systems, designed to capture the interactions between the economy, society and the environment.[20,21] They provide a means to represent the coupled energy-economy-land-climate system at varying levels of detail. IAMs differ significantly in geographic, sectoral, spatial and temporal resolution, reflecting variations in model scope, assumptions and methodological approaches. These differences influence how IAMs represent technological options, policy interventions, land-use constraints and socioeconomic dynamics.

IAM scenarios are a key tool for exploring plausible futures consistent with climate policy objectives, such as the temperature goal of the Paris Agreement. They do not claim and are not designed to be predictions of the future; rather, they provide quantified estimates of future changes consistent with a wide variety of assumptions about drivers of that change, such as population, GDP, technology costs and the pending availability of new technologies.[22,23] Unlike simulation models, IAM scenarios illustrate a range of possible cost-effective pathways, enabling policymakers and researchers to evaluate how different combinations of three elements – emissions reductions, residual emissions and CDR – can contribute to achieving temperature targets. By examining multiple scenarios, IAMs provide insights into the timing, scale and trade-offs of interventions required to limit global warming, highlighting which strategies are most feasible, which may pose risks and how different sectors and regions interact under alternative policy and technology pathways.

In this chapter, scenarios are considered compatible with the Paris Agreement if they limit global warming to well below 2°C (we consider such scenarios to be "well below" if they have a median peak temperature between 1.6°C and 1.8°C) and reach 1.5°C (with at least 50% probability) by the end of the century. All Paris-compatible pathways we assess involve a temporary overshoot, where warming surpasses 1.5°C in the early 2030s before being brought back below the threshold later in the century through further emissions reductions and accelerated CDR strategies. Evaluating overshoot pathways that return warming to 1.5°C by 2100 is important because doing so illustrates the required timing and scale of CDR deployment, the associated risks to ecosystems and societies, and the potential trade-offs inherent in restoring the climate trajectory.

8.1 Temperature, emissions and CDR

We assess three types of scenarios: those (1) consistent with current Targets & Pledges (i.e. current ambition), (2) with Highest Possible Ambition and (3) with a ten-year delay in Highest Ambition (see Figure 8.1). Our assessment does not include scenarios of current policies, which would result in significantly higher estimates of temperature increase compared to what countries have pledged as part of their overall climate ambition, as well as lower levels of CDR.

Prior research has estimated that current NDCs and LT-LEDSs result in a temperature increase between 1.8°C and 3°C by the end of the century.[24,25] In the Targets & Pledges scenarios, modelled warming reaches between 1.7°C and 2.7°C by 2100, broadly consistent with prior literature, even with the assumption that the United States no longer pursues federal climate action (see Chapter 5). However, global emissions do not reach net-zero CO_2 levels in most Targets & Pledges scenarios, meaning that global temperatures would continue to rise, albeit at a much more gradual pace, beyond 2100. Globally, scenarios consistent with Targets & Pledges scale up CDR at a slower pace compared to the Highest Possible Ambition scenarios, showing 2030 and 2035 annual median removals of 2.4–3.1 $GtCO_2$ (see Table 8.2) compared to approximately 2.2 $GtCO_2$ per year removed today (see Chapter 7). Even in these scenarios, novel CDR reaches gigatonne-scale deployment by 2050 (ranging between 0.6 and 4.2 $GtCO_2$ per year).

In scenarios that represent the Highest Possible Ambition – in other words, how quickly the world could reduce GHG emissions subject to technoeconomic feasibility and sustainability constraints but assuming full buy-in by all nations – global temperature peaks between 1.7°C and 1.8°C around 2050, consistent with the time of net-zero CO_2 in these scenarios. In the near-term, emissions reductions play the strongest role in overall mitigation, with 15.9 $GtCO_2$ per year of reductions by 2035 compared to 2020, while median CDR scales up to 3.9 $GtCO_2$ per year during the same period. When these scenarios achieve net-zero CO_2, 7.1–13.3 $GtCO_2$ per year of CDR balances remaining emissions (about 56% through conventional CDR and 44% through novel CDR). Starting from 2023, the last year for which we have historical data, the cumulative effort to achieve net-zero CO_2 is due largely to CO_2 emissions reductions (84% median, 80%–91% range) as compared to CDR, which plays an important, but smaller, role (16% median, 9%–20% range).

CDR and emissions levels ($GtCO_2$ per year) for assessed scenarios

Scenario	Type	2030	2035	2050	2100	Net-zero CO_2
Targets & Pledges	Conventional CDR	2.4 (2–2.9)	3 (2.3–3.4)	4.3 (2.3–8.3)	4.7 (1.5–9.1)	Not achieved in most scenarios
	Novel CDR	0 (0–0.1)	0.1 (0–0.3)	1.6 (0.6–4.2)	6.1 (1.4–11.2)	
	Total CDR	2.4 (2.1–3)	3.1 (2.4–3.6)	5.9 (3.1–10.2)	12 (3.9–16.1)	
	Change in CO_2 emissions from 2020	-0.6 (-4.6–3.1)	-4.6 (-10.8 to 1.3)	-25.1 (-29.6 to 16.6)	-36.4 (-40 to 19.5)	
	Residual GHG emissions	54.6 (52–59.2)	49.9 (41–57.4)	30.6 (24.3–40)	25.4 (18.6–37.6)	
Highest Ambition	Conventional CDR	2.6 (2.3–3.2)	3.4 (2.5–4)	5.6 (3.3–8.4)	6 (2.2–8.7)	6 (3.3–8.4)
	Novel CDR	0.1 (0–0.3)	0.4 (0–0.6)	3.5 (0.9–6.4)	9 (4.7–17.8)	4.8 (2.5–8.1)
	Total CDR	2.9 (2.3–3.3)	3.9 (2.7–4.1)	8.8 (6.5–13.3)	15.3 (9.2–24.7)	10.9 (7.1–13.3)
	Change in CO_2 emissions from 2020	-7.1 (-10.4 to 0.6)	-15.9 (-19.4 to 9.2)	-36.7 (-38.8 to 34.5)	-46.3 (-53.6 to 42.7)	-40.7 (-44.8 to 37.2)
	Residual GHG emissions	50.2 (41.1–56.1)	35.8 (32.5–47.2)	18.6 (15.5–25.9)	13 (9.9–14.3)	15.9 (13.2–21.4)
Delayed Ambition	Conventional CDR	2.4 (1.6–2.9)	3 (2.1–3.4)	4.4 (3–7.7)	6.7 (3.7–8.7)	5.9 (3.8–7.7)
	Novel CDR	0 (0–0.1)	0.2 (0–0.3)	2.2 (0.7–6.6)	16.7 (8–23.6)	6.1 (3.1–9)
	Total CDR	2.5 (1.7–3)	3.1 (2.3–3.6)	7 (4.9–14.3)	23.6 (14.8–28.2)	12.3 (8.3–14.8)
	Change in CO_2 emissions from 2020	-0.7 (-4.6–3.1)	-4.6 (-11.5 to 1.3)	-29.5 (-40.2 to 23.5)	-55 (-69.9 to 42.1)	-40.3 (-44.9 to 37.3)
	Residual GHG emissions	54.2 (51.7–59.2)	49.6 (40.1–57.4)	25.4 (14.2–35.4)	11.9 (5.8–17.4)	20.3 (14.2–24.3)

Table 8.2 *Note: Values show median (minimum – maximum) across models. Values reported as "Net-zero CO_2" are reported in different years for each model consistent with when that model's scenario achieves this milestone. CDR levels are harmonized to values from Chapter 7 to compare scenario values with latest deployment estimates.*

Delayed Ambition scenarios align with current targets in NDCs until 2035 and then rapidly accelerate towards maximum ambition, with temperature peaks between 1.7°C and 2.0°C; a decade of delay in mitigation ambition means an additional 0.15 °C of increased temperature and associated impacts (median across scenarios). Both emissions reductions and CDR levels advance quickly in these scenarios after 2035, with CDR reaching up to 8.3–14.8 $GtCO_2$ when net-zero CO_2 emissions are reached, and temperature peaks, between approximately 2047 and 2059. These scenarios see the largest volume of novel CDR at net-zero CO_2 emissions (3.1–9 $GtCO_2$ per year) due primarily to a delay in the reduction of sources of GHGs and the legacy of past emissions that have not been reduced as quickly as in the Highest Ambition scenarios. Different models show varying limits for how quickly these technologies can deploy and result in reduced net emissions.

Both the Highest Ambition and Delayed Ambition scenarios continue to mitigate residual sources of emissions and deploy additional CDR to achieve temperature drawdown after achieving net-zero CO_2 emissions. By 2100, these scenarios achieve deeply net-negative CO_2 emissions and further reduce non-CO_2 emissions, particularly methane, and thereby reduce temperatures below their peaks by around 0.24°C–0.37°C and 0.22°C–0.46°C, respectively. The Delayed Ambition scenarios have higher levels of annual CDR after achieving net-zero CO_2, and they remove around 28% more carbon cumulatively between the time of net-zero CO_2 and 2100, compared to the Highest Ambition scenarios – primarily through novel CDR. This higher CDR deployment reflects the higher peak warming and higher cumulative gross emissions in the Delayed Ambition scenarios – and therefore a greater need for CDR to counterbalance the cumulative warming from those emissions to return to 1.5°C or below by 2100.

The scenarios we assess use standard scientific modelling approaches to account for carbon emissions and conventional CDR on land. Countries, however, produce national emissions inventories using different accounting approaches based on the ability to physically measure and infer carbon flux on land (see Chapter 7).[26] Previously reported estimates[27] show that benchmarks like the year of net-zero CO_2 would occur roughly five years earlier if using NGHGI accounting. Even though these benchmarks appear more ambitious when using national inventory accounting, the underlying level of mitigation action in scenarios remains the same – the only difference is how countries account for emissions, including some removals that the scientific community considers to not be due to direct human influence (which are also excluded in Chapter 7's estimate of current removal levels). Critically, if all countries in the world achieved their climate targets in the current NGHGI frameworks, they would fail to meet their collective global temperature goal.

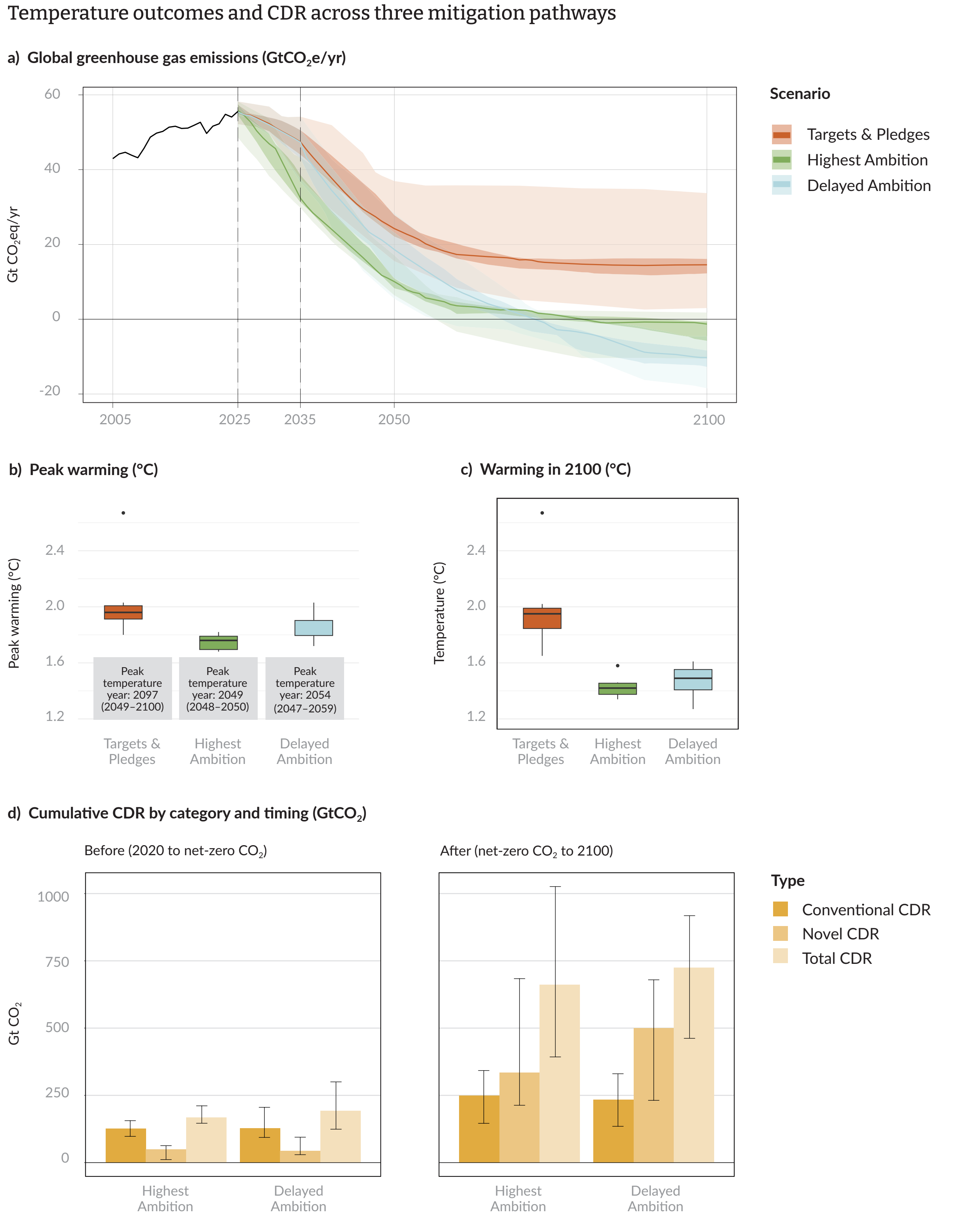

Figure 8.1 *(a) Historical GHG emissions from the Emissions Database for Global Atmospheric Research (EDGAR) (2005–2024)[28] followed by GHG emissions across all modelled scenarios (2025–2100), (b) peak temperature levels and median net-zero CO_2 emissions year per scenario, (c) temperature levels in 2100 per scenario, and (d) cumulative CDR deployed across models at the time of net-zero CO_2 and from net-zero CO_2 to the end of the 21st century. Solid lines in panel (a) depict the median scenario, and light shaded areas depict the minimum and maximum scenario values, and dark shaded areas represent the interquartile range. Bars in panels b, c and d depict the median scenario and whiskers depict the minimum and maximum scenario values. Individual data points in panel (b) depict outliers. Bars in panel (d) depict the median scenario and whiskers depict the minimum and maximum scenario values.*

All pathways present different challenges in terms of socioeconomic feasibility and sustainability. The overall level of CDR needed to achieve the necessary net-negative CO_2 emissions is most affected by the level of residual emissions – that is, the gross positive emissions at and after the level of net-zero CO_2 emissions. These differences illustrate how early action can reduce long-term reliance on CDR strategies, whereas delayed mitigation amplifies the need for sustained net-negative emissions later in the century.

8.2 CDR portfolio trade-offs and opportunities

The three pathways (Targets & Pledges, Highest Ambition and Delayed Ambition) diverge in both their projected 2100 system configurations and the trajectories leading to them. While mid-century outcomes (around 2050) remain relatively similar across scenarios due to shared near-term constraints and inertia in energy and land systems, differences in mitigation timing lead to substantially divergent system transformations in the second half of the 21st century. These differences reflect the cumulative influence of mitigation timing on energy, land use, food systems and carbon management. As IAMs incorporate a broader portfolio of mitigation technologies and more detailed CDR methods, scenario outcomes show increasing variability across models due to differences in modelling strategies, input assumptions, technology availability and system representations (see Technical Annex 8.2).

Across the three scenarios, CDR deployment grows over time, but the scale and composition vary significantly with mitigation ambition and portfolios (see Figure 8.2), leading to increased divergence in removal levels after 2050. Pathways that delay emissions reductions require substantially larger removals later in the century and rely heavily on novel CDR methods. This reflects both the limited and increasingly constrained potential of conventional CDR options due to land availability, sustainability limits and competing demands, as well as the need to compensate for higher cumulative emissions. By contrast, earlier mitigation reduces the overall removal requirement, allowing for a comparatively slower scale up of CDR deployment and a more diversified portfolio of CDR options.

In the Targets & Pledges scenarios, CDR increases but remains at the lowest levels of the three scenarios, rising from 2.4–3.6 $GtCO_2$ per year in 2035 to 3.1–10.2 $GtCO_2$ per year in 2050, and reaching around 3.9–16.1 $GtCO_2$ per year by 2100. Near-term removals are dominated by conventional land-based methods (52%–84% of total CDR in 2050, median 75%): afforestation, reforestation and forest management dominate (48%–81% by mid-century, median 71%), with smaller contributions from durable wood products. Novel CDR methods such as BECCS, DACCS and enhanced weathering remain limited until later in the century. By contrast, the Highest Ambition scenarios show deployment of CDR earlier and more steadily, reaching 2.7–4.1 $GtCO_2$ per year in 2035, 6.5–13.3 $GtCO_2$ per year by 2050, and 9.2–24.7 $GtCO_2$ per year by 2100. In these scenarios, a larger share of emissions reductions is achieved through earlier mitigation, relative to Delayed Ambition scenarios and Targets & Pledges scenarios, which reduces the total need for CDR and shifts the portfolio towards a more balanced mix of conventional (42%–89%, median 61%) and novel (11%–58%, median 39%) methods by 2050. This allows for a more diversified portfolio combining conventional and novel methods.

By the middle of the 21st century, the Delayed Ambition scenarios deploy slightly lower amounts of CDR compared to the Highest Ambition scenarios. But by the end of the century, delaying mitigation shows the strongest increase in CDR methods. After tracking close to Targets & Pledges until mid-century, removals surge after 2050, peaking at 14.8–28.2 $GtCO_2$ per year by 2100, the highest across all scenarios. This increase in 2100 in Delayed Ambition scenarios is associated with a higher share of novel CDR methods (reaching approximately 54%–86% of total CDR by 2100, median 69%). This expansion in 2100 tends to be driven by DACCS (5%-41%, median 21%) and on biomass-based CDR, particularly BECCS (17%–49%, median 31%); these methods are complemented by substantial expansion of enhanced weathering (0%–18%, median 9%); ocean-based CDR (e.g. DOCCS, alkalinity enhancement of water bodies and ocean fertilization) (0%–12%, median 7%); biochar (2%–8%, median 3%); durable wood products (1%–2% median 1%); and bio-oil storage (0%–9%, median 2%). In these scenarios, the limited availability and saturation of conventional land-based options, combined with higher removal requirements, necessitates a stronger scale-up of novel CDR.

Portfolio of CDR methods across three mitigation pathways at 2035, 2050 and 2100

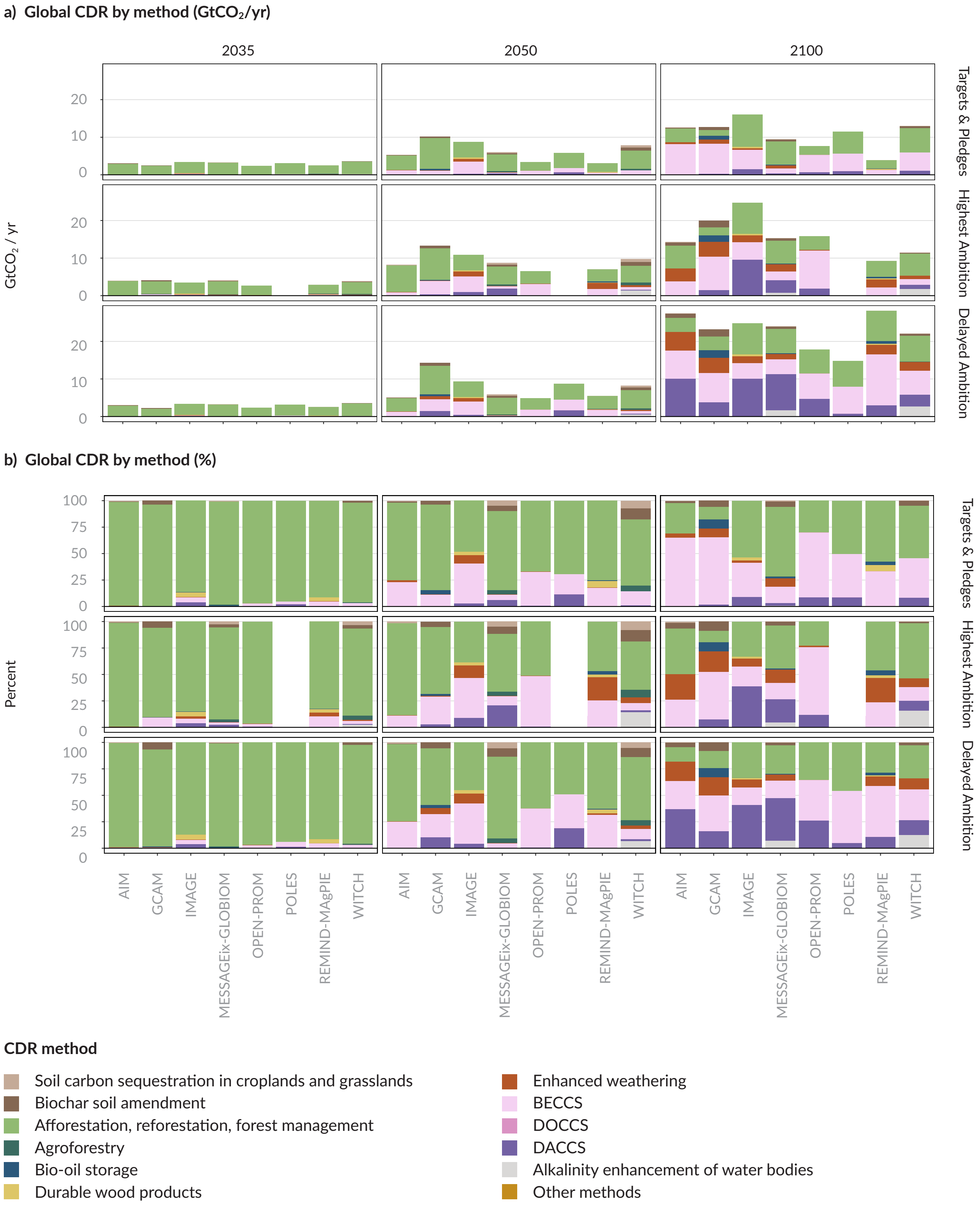

Figure 8.2 *Global carbon removal by method in 2035, 2050 and 2100 across three scenarios: Targets & Pledges, Highest Ambition and Delayed Ambition. Each panel shows the level of annual deployment of CDR for all assessed modelling frameworks. Panel (a) shows absolute values ($GtCO_2$ per year) and (b) shows relative shares (% of total CDR). The POLES Highest Ambition scenario is not displayed because the submitted version did not pass screening for CCS scale-up feasibility. Future assessments will include an updated version of the scenario.*

All scenarios show the deployment of nascent technologies and methods at very large scale, which can raise considerations around their feasibility (see Figure 8.3). Between 2025 and 2100, cumulative geological storage ranges from 108–652 $GtCO_2$ in Targets & Pledges (median 344 $GtCO_2$); 137–1,031 $GtCO_2$ in Highest Ambition (median 376 $GtCO_2$); and 284–990 $GtCO_2$ in Delayed Ambition (median 603 $GtCO_2$) (see Figure 8.3a). Although these volumes represent a large infrastructure deployment, they remain below estimates of prudent global geological storage potentials reported in the literature.[18] However, these values should be considered with caution, as they represent a sustained and continued use of CCS beyond 2100, when the time-horizon of these models ends, and they could well exceed prudent planetary limits soon thereafter. Annual CO_2 injection rates also increase rapidly over time, but the timing of storage deployment differs across scenarios (see Figure 8.3b). By 2050, median CO_2 storage reaches approximately 1.8 $GtCO_2$ per year (full range 1.1–6.8 $GtCO_2$ per year) in Targets & Pledges; 3.2 $GtCO_2$ per year (1.2–9.5 $GtCO_2$ per year) in Highest Ambition; and 2.7 $GtCO_2$ per year (0.7–9.6 $GtCO_2$ per year) in Delayed Ambition. By 2100, the impacts of delaying ambition become more evident: the median storage reaches approximately 9 $GtCO_2$ per year (1.8–14.2 $GtCO_2$ per year) in Targets & Pledges; 7.5 $GtCO_2$ per year (2.8–21.5 $GtCO_2$ per year) in Highest Ambition; and 15.1 $GtCO_2$ per year (10.5–21 $GtCO_2$ per year) in Delayed Ambition scenarios. Meeting these annual storage rates requires the rapid expansion of CO_2 transport and geological storage infrastructure, including pipelines, injection wells and monitoring systems, raising important feasibility challenges.[29–34]

The pace and scale of infrastructure deployment for novel CDR methods is large across all scenarios. DACCS grows from a median of 0.003 $GtCO_2$ in 2030 to 0.03 $GtCO_2$ in 2040, and BECCS from a median of 0.02 $GtCO_2$ to 0.25 $GtCO_2$ in the same decade. In the near-term (2030–2040), DACCS grows at a median compound annual growth rate of about 26% across models (full range 0.5%–50%) (see Figure 8.3c). BECCS shows a similar steep growth, with a median compound annual growth rate ranging between 25% and 37% across scenarios (full range 11%–87%). These high growth rates partly reflect very small initial deployment levels. As a result, even similar absolute increases translate into large percentage changes. This means that the variation in growth rates is driven more by differences in model frameworks than scenario assumptions.

Energy requirements for all carbon management – including fossil CCS and CCU as well as CDR – remain modest through 2050 across all scenarios (see Figure 8.3d): generally below 2% of final energy in Targets & Pledges (median of 0.1%); between 0.4% and 3.2% in Highest Ambition (median of 0.8%); and between 0% and 5% in Delayed Ambition (median of 0.3%). This can roughly be compared with, for example, data centre energy consumption – which currently requires 0.36% of total final energy and may double by 2030, according to some estimates.[35] By 2100, the burden increases most sharply in Delayed Ambition pathways, with all models demanding above 3% of final energy (and a median of 5.4%) for carbon management (and as high as 17%), similar in magnitude to the share of global annual final energy consumption for the European Union or Japan today.

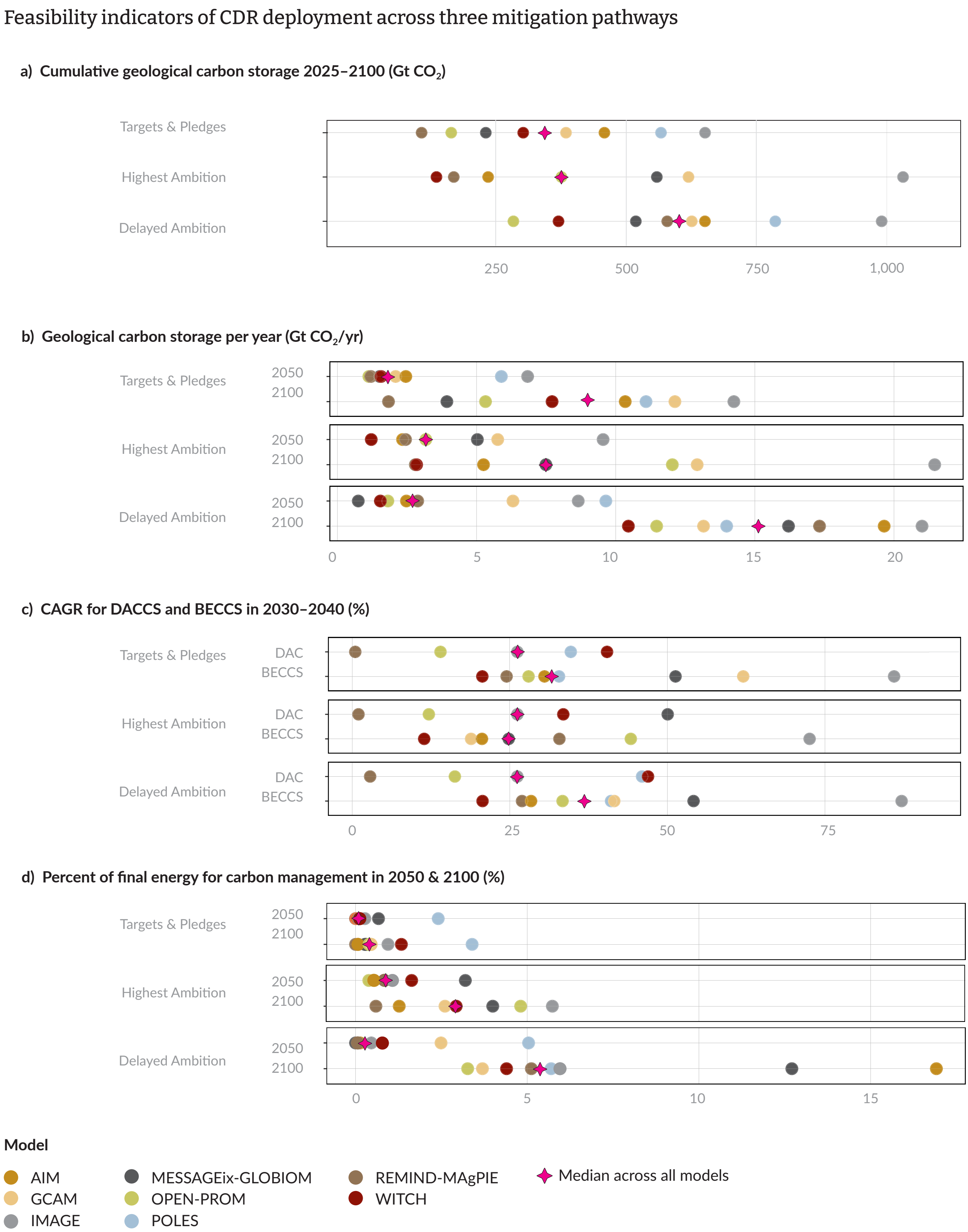

Figure 8.3 *Feasibility indicators for each assessed modelling framework and scenario. Panel (a) cumulative carbon storage (2025–2100), (b) carbon storage in 2050 and in 2100, (c) DACCS and BECCS compound annual growth rate (CGAR) (2030–2040), and (d) share of final energy used for carbon management. Individual model values are shown as well as the median across all models for each indicator.*

Land-use outcomes vary widely across models due to differences in socioeconomic, agricultural and land-use assumptions, with model spread often exceeding differences between mitigation scenarios (see Figure 8.4a). By 2100, cropland in Targets & Pledges ranges from roughly 800–1,950 Mha, while Highest Ambition scenarios generally allocate less land for crops (530–1,800 Mha) as productivity improvements and dietary shifts reduce land demand. Delayed Ambition, on the other hand, shows the largest divergence (350–1,900 Mha), indicating fundamentally different assumptions about agricultural intensification, dietary change and the scale of land-based carbon removal. Forest area increases in all scenarios by 2100 compared to baseline years; it reaches 4,009–4,561 Mha in Targets & Pledges; 4,367–4,963 Mha in Highest Ambition; and 4,269–5,067 Mha in Delayed Ambition – with the highest values in some delayed pathways reflecting stronger late-century reliance on conventional land-based CDR (see Figure 8.4b).

Energy system composition also interacts with land-use outcomes (see Figure 8.4c). Targets & Pledges scenarios retain the highest dependence on fossil fuels, which serve as a major energy source in 2050, ranging from 35%–56% of the total (median 47%) and remaining substantial in 2100 at roughly 17%–36% (median 29%). Highest Ambition scenarios generally show lower fossil fuel use throughout the century, declining from 21%–39% (median 25%) of total primary energy in 2050 to 9%–19% (median 14%) by 2100. Delayed Ambition scenarios show high fossil fuel use around mid-century (30%–52% of primary energy, median 36%), but decline more sharply thereafter, reaching 0%–15% (median 13%) by 2100. In some scenarios, residual fossil fuel use is coupled with CCS. Nevertheless, this reliance on fossil fuels may be associated with upstream environmental impacts and have implications for energy security for import-dependent countries.

Fossil fuel dependence is partly replaced by greater reliance on biomass and other low-carbon energy sources (see Figure 8.4d). Biomass primary energy in 2050 spans 8%–21% (median 13%) of primary energy in Targets & Pledges, 10%–23% (median 15%) in Highest Ambition and 10%–27% (median 15%) per year in Delayed Ambition. By 2100, biomass use rises slightly to 9%–26% (median 15%) per year in Targets & Pledges, decreases slightly to 10%–24% (median 14%) per year in Highest Ambition and rises to 12%–32% (median 17%) per year in Delayed Ambition. Such levels of biomass deployment may approach sustainability thresholds discussed in the literature (e.g. in the range of 100–150 EJ) and raise concerns regarding land availability, impacts on local ecosystem services and food competition.[36,37]

Sustainability indicators of CDR deployment across three mitigation pathways in 2050 & 2100

Figure 8.4 Sustainability indicators for each assessed modelling framework. Panel (a) land cover from crops, (b) land cover from forests, (c) share of fossil fuels (i.e. coal, oil and gas) in primary energy, and (d) share of biomass in primary energy. Individual model values are shown as well as the median across all models for each indicator.

Taken together, these patterns point to a fundamental structural insight: mitigation timing strongly shapes the scale, feasibility and sustainability of CDR deployment. Early and sustained ambition to reduce sources of emissions lowers long-term dependence on novel CDR methods, whereas delay creates higher reliance on CDR, greater uncertainty, and stronger climate impacts on land and food systems. This increases infrastructure requirements, energy demand and pressure on land systems. At the same time, the extent to which land-based CDR constitutes a constraint or a viable mitigation option depends on broader transformations in food systems. Improvements in agricultural productivity, shifts towards less land-intensive diets and reductions in livestock production can substantially lower baseline land demand, thereby enabling the deployment of land-based CDR without necessarily compromising food security. In this sense, action on food systems is a key enabler of sustainable CDR deployment rather than a competing objective. Conversely, in pathways where such transformations are limited, land-based CDR is more likely to intensify competition for land and increase risks to food systems.

Although CDR plays a role in all pathways, the balance between emissions reduction, land management and carbon removal varies substantially depending on the timing and ambition of climate action, highlighting the need for integrated policy approaches that jointly address mitigation, food systems and land use rather than treating them as separate domains.

8.3 Country and regional CDR pathways

Achieving the temperature goal of the Paris Agreement will require differentiated emissions reductions across countries and regions. National pathways are an important complement to global scenario evidence on options for limiting peak temperature while meeting Sustainable Development Goals (SDGs) as they provide higher spatial granularity and context-specific perspectives. The degree to which global interactions, such as extraterritorial CO_2 transport and storage, are considered in national models varies across different frameworks. In many cases, modelling studies are focused on national actions consistent with domestic priorities. Whereas a global model may show large CDR deployment in a given region consistent with global cost effectiveness, national models may show substantially different results. These differences may be related to national priorities considered by modellers with more contextual understanding or different considerations of sustainability and feasibility, including land availability, geological storage capacity, energy systems, water demand, ecologic impacts and economic structure.[34,38,39]

Over 100 countries and the European Union have committed to achieving net-zero emissions during this century, either on a GHG or CO_2 basis, and 194 are parties to the Paris Agreement. While CDR is necessary to achieve net-zero targets, most governments have yet to clearly state plans for the scale, timing and portfolio of CDR in their national pathways (see Chapter 5). Existing frameworks often emphasize net-emissions targets while providing limited information on the role of CDR or the level of residual emissions and why those are considered too hard to transition.[25,40] Because of these gaps in evidence, scenarios from national models can provide insights into different pathways for meeting climate goals and the role of CDR in these pathways.

As in the global scenario exercise, we invited national and regional modelling teams to develop targeted scenarios using a consistent protocol: (1) Targets & Pledges, (2) Highest Ambition and (3) Delayed Ambition. For the Targets & Pledges scenario, teams interpreted NDCs and announced pledges based on their expert judgment. Country modelling teams also made their own expert judgments in terms of what is either feasible or sustainable within their individual country contexts (e.g. what it means to achieve Highest Ambition). Five teams using the Global Change Analysis Model (GCAM) framework provided scenarios with region-specific models of China, Europe, India, Saudi Arabia and the United States, collectively responsible for over half of current GHG emissions.[41] As with global models, country-level modelling frameworks are also increasing their representation of various CDR methods (see Table 8.3); all models represent afforestation and reforestation along with BECCS, most models represent DACCS, and other methods have more limited representation. Importantly, as with the global scenario exercise, regional model results reflect different model structures and modeller interpretations of the protocol. For example, some models have shorter time horizons, ending before 2100 (e.g. in 2050 for GCAM-Europe and 2070 for GCAM-India).

While global IAM pathways often show higher late-century CDR deployment under delayed mitigation due to the need to compensate for higher cumulative emissions, the regional models do not necessarily assume a fixed regional carbon budget. Thus, these models may assume that other countries or regions pursue higher climate ambition – such as achieving net-negative emissions sooner and to a higher degree – in order to achieve an overall global temperature goal. As a result, a Delayed Ambition scenario does not necessarily lead to higher negative emissions by the end of the century. Furthermore, some regional implementations of the Targets & Pledges scenario reflect current policy frameworks rather than strict carbon budget constraints, meaning that land sinks or non-CO_2 mitigation are not always fully integrated into the target formulation.

CDR methods featured in national models and assessed in this chapter

Model	Afforestation, reforestation, forest management	BECCS	DACCS	EW	Biochar soil amendment	Ocean-based methods	Long-lived materials
GCAM-China	✗	✗	✗	✗			
GCAM-Europe	✗	✗	✗				✗
GCAM-India	✗	✗					
GCAM-KSA	✗	✗	✗				
GCAM-USA	✗	✗	✗	✗	✗	✗	✗

Table 8.3

Regional emissions and CDR pathways

Across the regional pathways, GHG emissions decline and CDR deployment increases over the modelled time horizons, although the pace and magnitude differ across scenarios and regional contexts. Figure 8.5 presents GHG emissions and CDR trajectories across the five regional models. Some teams interpreted the protocol in slightly different ways. For example, the Targets & Pledges trajectory for the European Union is more closely aligned with the implementation approach of current policies. Most modelling teams report all GHGs save GCAM-India, which only reports CO_2 emissions.

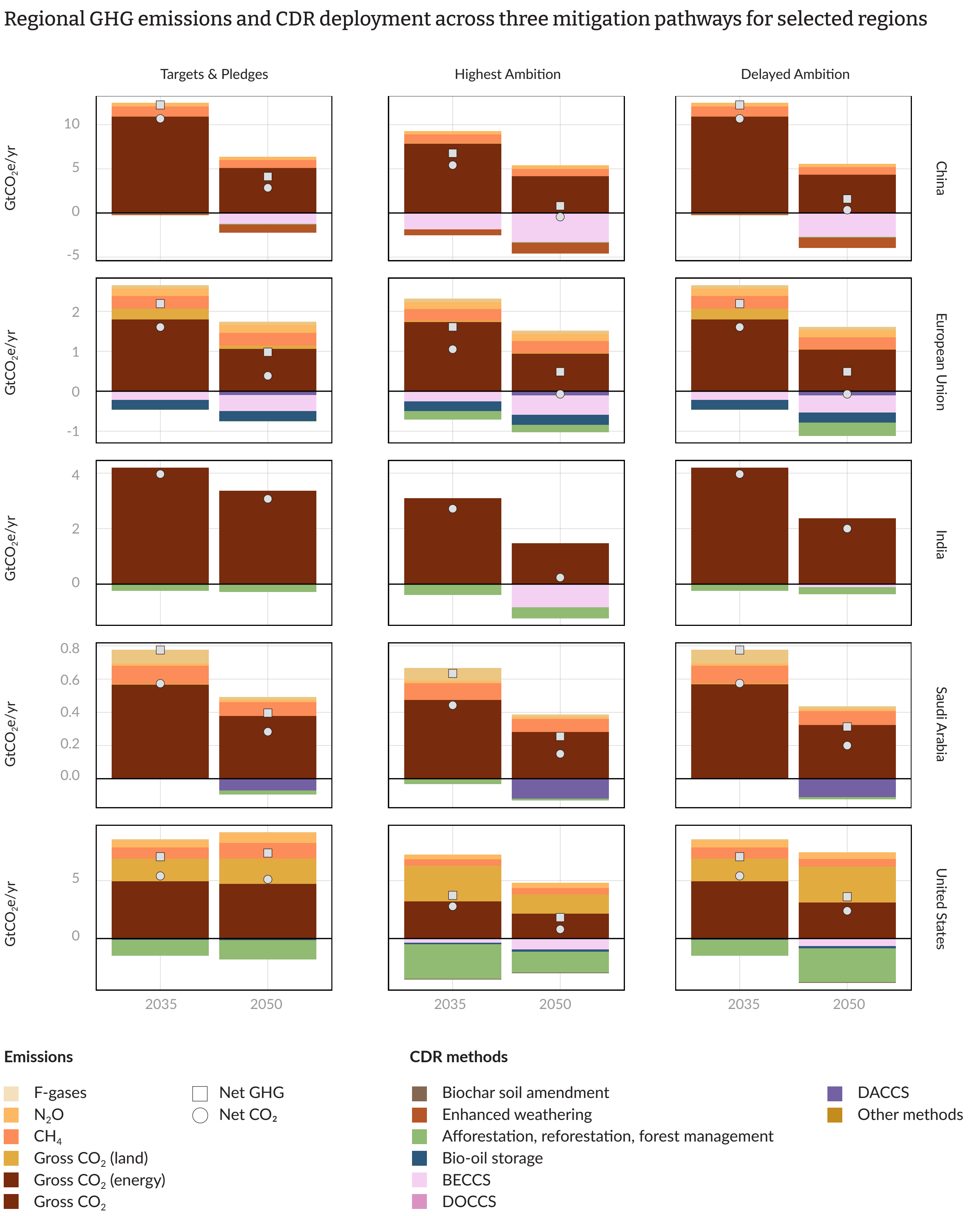

Figure 8.5 *Levels of gross emissions and gross removals for each modelled region in 2035 and 2050. Panel (a) China, (b) European Union, (c) India, (d) Saudi Arabia, and (e) the United States. Emissions by gas and removals by method ($GtCO_2e$ per year) are shown. Net values are shown as individual markers in each panel.*

China

China aims to achieve carbon neutrality before 2060, but interpretations differ as to whether this target encompasses only CO_2 or all GHGs. The GCAM-China team interpreted this to mean that scenarios reach net-zero GHGs around 2060. GHG emissions decline by 66% between 2035 and 2050 under the Targets & Pledges scenario, and much faster in the Highest Ambition pathway, falling by about 88%. Net-zero CO_2 emissions occur earlier in the Highest Ambition scenario (2047) than in Delayed Ambition (2053) and Targets & Pledges (2057). CDR deployment expands rapidly between 2035 and 2050 across all three scenarios: removals grow from 0.2 $GtCO_2$ per year to 2.2 $GtCO_2$ per year in the Targets & Pledges scenario, from about 2.5 $GtCO_2$ per year to 4.6 $GtCO_2$ per year in the Highest Ambition pathway, and from 0.2 $GtCO_2$ per year to almost 4 $GtCO_2$ per year in the Delayed Ambition scenario (which shows the fastest increase across the three scenarios). Most removals are provided by novel CDR methods (especially BECCS and enhanced weathering), which account for more than 94% of total CDR across scenarios and years. These results reflect one set of modelled pathways and remain subject to uncertainties in the evolution of CDR-related policies in China.

European Union

The European Union has a target for net-zero GHG emissions by 2050. For the Targets & Pledges scenario, emissions up to 2030 are fully determined by explicit policies, which stay constant beyond 2030, supplemented by an energy CO_2 target for 2050. In Targets & Pledges, CO_2 emissions from LULUCF are left unconstrained, meaning that model results do not necessarily reach the EU's stated target. However, land use CO_2 is included in the target for the Delayed Ambition and Highest Ambition scenarios. Between 2035 and 2050, GHG emissions decline by about 55% under Targets & Pledges – which focuses on current EU policies rather than the overall net-zero target – compared with 70%–78% in the Highest Ambition and Delayed Ambition scenarios, reflecting strong mitigation efforts. CDR deployment increases modestly in the European Union. Total removals rise from roughly 0.5–0.7 $GtCO_2$ per year in 2035 to about 0.8–1.1 $GtCO_2$ per year by 2050, depending on the scenario. In contrast to China, the share of conventional land-based CDR is comparably larger, although novel methods still represent the majority of removals by mid-century in most pathways (over 70% of the total, mostly via BECCS and bio-oil storage).

India

India has set a goal of achieving net-zero emissions by 2070. As with China, there are differing interpretations of whether this target covers CO_2 only or all GHGs. The GCAM-India team interpreted this target to only cover CO_2. Compared to China and the European Union, scenarios show slower CO_2 emissions reductions (the model results do not include other GHGs), particularly under the Targets & Pledges scenario. Between 2035 and 2050, CO_2 emissions fall by about 23% under Targets & Pledges, compared to 91% under Highest Ambition and 50% under Delayed Ambition. Despite these reductions, none of the scenarios reach net-zero CO_2 within the model horizon of 2070. CDR deployment remains modest in the near-term but increases more rapidly under Highest Ambition scenarios. Total removals rise from roughly 0.4 $GtCO_2$ per year in 2035 to about 1.2 $GtCO_2$ per year by 2050 in the Highest Ambition pathway, while they remain in the range of 0.2–0.4 $GtCO_2$ per year in the other two scenarios. Conventional land-based methods dominate early deployment (>97% of total CDR), with the share of novel CDR only surpassing 50% in the Highest Ambition scenario by 2050 (namely BECCS).

Saudi Arabia

Saudi Arabia has pledged to achieve net-zero GHG emissions by 2060, and all scenarios achieve this milestone. GHG emissions decline by about 49%–60% between 2035 and 2050, depending on the pathway, with slightly faster reductions under the Highest Ambition scenarios, which reach net-zero GHGs slightly earlier (around 2058) than the official pledge. CDR deployment in 2035 starts from a very small base (almost zero in the Targets & Pledges and Delayed Ambition scenarios, and roughly 0.03 $GtCO_2$ in the Highest Ambition scenario) but increases steadily over time across all pathways. By mid-century, removals rise to roughly 0.10 $GtCO_2$ per year under Targets & Pledges, 0.13 $GtCO_2$ per year under Highest Ambition and 0.12 $GtCO_2$ per year under Delayed Ambition. Over 76% of removals by mid-century are provided by novel CDR methods (namely DACCS). This reflects the limited potential for land-based removals and the stronger role of engineered methods such as DACCS.

United States

In the United States, emissions decline in two scenarios but stay substantially net-positive under Targets & Pledges. Consistent with the country's exit from the Paris Agreement, GHG emissions slightly increase by about 4% between 2035 and 2050 under the Targets & Pledges scenario, compared with roughly a 51% decrease under Highest Ambition, and a 49% decrease in Delayed Ambition. The three pathways in the United States rely significantly on CDR deployment. Total removals increase from about 1.5 $GtCO_2$ per year in 2035 to 1.8 $GtCO_2$ per year in 2050 under Targets & Pledges (92% through conventional CDR). Under Highest Ambition, removals slightly decrease from 3.5 $GtCO_2$ per year in 2035 to 3 $GtCO_2$ per year in 2050 (60% through conventional CDR), as lower residual emissions decrease the reliance on CDR. In the Delayed Ambition scenario, CDR grows from 1.5 $GtCO_2$ per year in 2035 to 3.8 $GtCO_{2_2}$ per year in 2050 (77% through conventional CDR). Over time, the composition of CDR shifts, with conventional methods dominating deployment and novel CDR methods growing by mid-century.

Insights, limitations and implications for CDR deployment across countries and regions

Results across regional pathways feature a diversity of CDR methods at net zero and beyond. While regional scenarios are only implemented in a single framework (i.e. GCAM), introducing certain modelling biases and footprints, scenarios differ significantly based on both national and global assumptions developed by individual teams. In the Highest Ambition pathways, emissions decline substantially between 2035 and 2050, with GHG emissions reductions ranging from about 51% to 88% depending on the region. Net-zero CO_2 is reached earliest in the European Union (around 2046), followed by China (around 2047) and the United States and Saudi Arabia (around 2057). India approaches but does not reach net-zero within the model horizon of the submitted scenarios (through 2070). The scale of CDR in the Highest Ambition scenarios also varies considerably across regions. In these pathways, removals in 2050 range from about 0.13 $GtCO_2$ per year in Saudi Arabia (increasing by around 300% between 2035 and 2050) to around 4.6 $GtCO_2$ per year in China (around 84% increase), with moderate levels in the United States (3.0 $GtCO_2$ per year, at similar levels in 2035), 1.0 $GtCO_2$ per year in the European Union (46% increase) and 1.2 $GtCO_2$ per year India (224% increase). All regions except the United States show a majority (68%–99%) for CDR from novel methods in the Highest Ambition scenarios.

The regional results illustrate how national targets and ambitions connect with global scenarios, but they should be interpreted with several limitations. Here, we assess a few scenarios from each country modelling team, while a broader range of scenarios exists across the integrated assessment modelling literature, including pathways developed with other model frameworks and alternative assumptions about technology development, policy ambition and socioeconomic conditions. Furthermore, the five regions examined here represent a subset of national circumstances. Many other countries face different resource constraints, institutional conditions and development priorities that shape their potential roles in scaling CDR globally.

We also represent a small snapshot of stylized assumptions of international interactions, and the deployment of CDR will certainly extend beyond the regions examined here and include broader international cooperation. One proposed mechanism not captured in this country-level analysis is international trading of carbon removal credits, in which countries with surplus removal capacity implement projects on behalf of those with limited domestic potential. Differences in resource availability, technological capacity and costs across regions suggest that large-scale CDR deployment may occur unevenly across regions and could involve increasing cross-border cooperation and international carbon management. When outcomes from country-specific analyses show systematically less climate action than in global scenarios, this implies that other nations would need to pursue even more ambitious climate strategies to achieve the same global temperature outcome.

National priorities and related scenarios may consider equity perspectives in the context of historical emissions, meaning that economic efficiency alone are unlikely to determine the preferred distribution of removals. Under the Paris Agreement, developed countries with greater financial and technological capacity are expected to support mitigation efforts in developing countries through climate finance, technology development and transfer, and capacity-building (Articles 9, 10 and 11). Accordingly, some countries may combine domestic CDR deployment with international cooperation, potentially including the use of internationally transferred mitigation outcomes under Article 6 of the Paris Agreement, to support global mitigation efforts as well as transferring technology and providing financial support to low- and middle-income countries with less historic carbon emissions.

8.4 Developing robust strategies despite uncertainties

The large volumes of CDR consistently deployed in deep mitigation pathways assessed in this chapter can give the impression of scientific certainty about robust landing zones for CDR in the medium and long term. In practice, current policies, investment flows and deployment trends in most regions remain substantially below those implied by these pathways, suggesting a significant gap between modelled feasibility and real-world implementation. At the same time, there are multiple dimensions of uncertainty – within the modelled mitigation pathways, in the interactions between CDR and the climate system, and in sociopolitical factors – that may be resolved over very different time frames. Understanding these uncertainties is essential for determining how deep mitigation pathways can appropriately inform the design of robust CDR deployment strategies and where critical knowledge gaps remain.

At a high level, the demand for CDR in any modelled pathway is shaped by exogenous inputs. These include the stringency of the climate target; the likelihood with which it should be achieved given current scientific understanding; and the objective function of the model – which typically prioritizes economic efficiency but can further be constrained by considerations like sustainability or equity.

Even with consistent high-level targets, CDR deployment varies significantly across different IAMs. This inter-model variation stems from differences in core model structure and parameterization. The modelled competition between emissions reductions and CDR is directly influenced by factors such as projected energy demand, assumed technology costs and discount rates for both abatement and removal, and the resulting carbon price. Consequently, how a model evaluates the relative competitiveness and resource demands of various options determines not only the total scale of CDR but also the composition of the resulting portfolio.

Differences in the composition of the CDR portfolio itself arises from several factors. First, the modelled representation of CDR methods is not uniform, and efforts by modelling teams to broaden the suite of represented technologies is actively underway. Second, even when a CDR method is included, its implementation may differ. For instance, models may represent different technological realizations (e.g. low- versus high-temperature DACCS) or parameterize BECCS options with varying efficiencies and costs, reflecting deep uncertainty inherent in novel technologies. Third, models incorporate different constraints on key resources. The representation of land-use dynamics, for example, dictates the potential for bioenergy and enhanced weathering on land, while differing assumptions about the practical availability and cost of geological storage directly limit the scale of CCS-based CDR methods.

While the amount of CDR in these scenarios is already substantial, it may represent a conservative estimate. The modelled demand could increase significantly when considering critical uncertainties in the Earth system response (see Box 8.2) and the sociopolitical implementation of emissions reduction efforts, which may limit the pace or depth of mitigation and thereby increase the need for CDR. Furthermore, the carbon budgets used in scenarios to limit warming to a given temperature are probabilistic – for example, returning to 1.5°C warming levels with a 50% chance is widely used to establish whether a pathway is consistent with 1.5°C. Such a pathway is equally likely to keep warming below 1.5°C as above it. In the case of a higher-than-expected peak warming response, additional CDR would be required to bring temperatures back down.

Sociopolitical realities present an additional, and perhaps larger, source of uncertainty. IAMs often assume idealized conditions to achieve emissions reductions, such as immediate and globally coordinated climate action, comprehensive carbon pricing across all sectors and GHGs, and frictionless markets. In practice, deviations from these assumptions – such as delayed ambition or incomplete participation – would likely result in higher residual emissions; the consequence would be an increased reliance on CDR to compensate for the shortfall. Moreover, the cost-optimal distribution of mitigation effort in scenarios is not necessarily aligned with national perceptions of fair mitigation effort.

Box 8.2 Earth system uncertainty in understanding of needed levels of CDR

The efficacy and long-term viability of CDR are subject to significant Earth system uncertainties that challenge the durability of stored carbon, particularly for land-based methods. Storage in forests and soils is inherently reversible and vulnerable to disturbances from wildfires, pests and insects, and drought,[42,43] which are intensified by climate-driven extreme weather events. At the same time, some Earth system responses, namely CO_2 fertilization and higher surface temperatures that accelerate vegetation growth, may enhance carbon uptake in certain regions. Taken together, these processes introduce substantial uncertainty in the net effectiveness of CDR methods, rather than a uniformly negative impact. While the scientific community is working to include these feedbacks into climate models, much of these effects are not represented in the coupled modelling frameworks that produce the scenarios assessed here.

Furthermore, the net benefit of land-based sinks is a function of the mitigation pathway itself. Ambitious scenarios that successfully lower atmospheric CO_2 also weaken the CO_2 fertilization effect, reducing the strength of the indirect land sink. This physical feedback means that a greater quantity of deliberate, direct CDR is required to achieve the same net carbon uptake compared to a pathway with less stringent mitigation – a dynamic that increases the burden on managed ecosystems. Nations that rely heavily on land to remove carbon may find that it is ultimately a source of emissions.[27]

Novel CDR methods, including DACCS and BECCS, are also constrained by climate feedbacks and Earth system interactions. DACCS, for instance, relies on energy- and material-intensive processes, often coupled with renewable sources. Its net removal efficiency can decline if regional heatwaves reduce energy output or water availability. Similarly, BECCS requires large-scale biomass production, which is affected by changes in temperature and CO_2 fertilization. These feedbacks mean that even novel removal methods are not fully immune to climate variability and extreme events, and their efficacy may be lower than modelled in IAM scenarios that assume stable operational conditions.

Broader uncertainties in the Earth system's response to net-negative CO_2 emissions further complicate reliance on CDR. Whether the climate-carbon cycle response is symmetrical (for example, if a unit of carbon removal before net-zero CO_2 is as effective as a unit of carbon removal after net-zero CO_2)[44,45] or how much additional warming may occur even with net-zero CO_2 emissions[46] are key areas of active scientific effort. Further, certain climate impacts may exhibit strong hysteresis or be effectively irreversible on human timescales.[47] If the fidelity of climate representation in IAMs lags behind the latest climate science, IAMs could underestimate the risks associated with overshoot pathways and the level of CDR needed to achieve a given climate target.

8.5 Outlook

Despite uncertainties and variations across models, the scenario evidence from this report shows some robust findings. CDR is deployed at the scale of multiple gigatonnes across all assessed scenarios, often at growth rates rarely observed historically for other innovative technologies, with the scenarios representing highest possible ambition deploying the most CDR by 2050. Conventional CDR on land plays a larger role than novel CDR to achieve net-zero CO_2 emissions. However, by the end of the century, novel CDR plays a stronger role in all scenarios, especially in those that model a ten-year delay in ambitious climate action. Of all novel CDR methods modelled, those relying on CCS – namely, BECCS and DACCS – make up the largest shares. However, enhanced weathering begins to play a stronger role in many scenarios after mid-century.

The scenario evidence in this report strengthens and confirms previous findings: in Highest Ambition pathways, limiting warming well below 2°C is achieved primarily through reducing sources of emissions (around 84% of total mitigation effort) while also deploying CDR (around 16% of total effort). Limiting warming to 1.5°C will take additional effort to achieve and sustain net-negative CO_2 emissions with CDR taking an even stronger role. Still, the scale up of CDR in the Highest Ambition scenarios is substantial – at the time that net-zero CO_2 emissions are achieved, around 11 $GtCO_2$ per year of CDR is balancing residual emissions, a five-fold increase from current levels. Rather than prescribing specific strategies, the results outlined above provide a basis for identifying key system-level implications and patterns that emerge consistently across scenarios.

1. Prioritizing emissions reductions to limit CDR dependence: A robust strategy is one that limits anticipated dependence on CDR by prioritizing direct emissions reductions. The most cost-effective abatement opportunities often lie in the energy sector and through sustainable land use management. Following the exhaustion of these options, strategic decisions arise regarding whether to offset remaining hard-to-abate emissions with limited, high-value CDR or to pursue more costly direct reductions in those sectors. From a risk management perspective, earlier and deeper emissions reductions can reduce exposure to potential CDR underperformance and the need for large-scale, net-negative emissions later in the century.

2. Accounting for underestimation in modelled CDR projections: The CDR deployment ranges found in IAM pathways may represent a lower bound on future requirements. This is because model scenarios often assume idealized conditions for achieving emission reductions, such as immediate and comprehensive global cooperation, which may not reflect real-world implementation challenges. Furthermore, unresolved physical risks, such as a stronger-than-expected climate response and its implications for losses and damages from climate change, could increase the amount of CDR needed to meet a given temperature target. Consequently, the CDR amounts in these scenarios

should be seen as lower bounds of CDR needed to achieve the global temperature outcomes reflected in these scenarios.

3. Enhancing robustness through a diverse CDR portfolio: The development and deployment of a broad CDR portfolio limits systemic risk by reducing reliance on any single option.[48] Individual CDR methods face distinct uncertainties, including physical risks that may constrain potential, techno-economic uncertainties that may affect cost and scalability, and possible negative side effects that could render large-scale and speedy deployment undesirable. Maintaining a portfolio of options provides flexibility to adapt as these uncertainties are resolved over time, enabling the selection of methods best suited to regional resources and societal preferences.

4. Recognizing implementation as a determinant of sustainability: The sustainability of a CDR project is determined not only by the scale of deployment but, critically, by how it is implemented and which social and environmental issues it may generate. In modelled scenarios, stylized assumptions may be made that assume CDR projects are implemented sustainably. However, sustainability cannot be assessed in isolation, as it depends on broader system dynamics across the economy, particularly interactions with food systems, land use and resource demand. For example, reforestation aiming for ecosystem restoration yields different outcomes than monoculture plantations. Similarly, enhanced weathering and biochar applications can either supply valuable nutrients or introduce trace metal contaminants depending on the rock mineralogy and the properties of the biochar feedstock. These implementation-specific details, which dictate the ultimate co-benefits or negative impacts of a project, are only partially represented in large-scale scenarios.

5. Establishing governance as an enabler of scale: The scale and pace of CDR deployment observed across scenarios imply the need for enabling policy and governance conditions,[49] even if these are not always explicitly represented in the modelling frameworks assessed in this chapter. Achieving the ambitious, near-term CDR deployment and upscaling found in mitigation scenarios is contingent upon having effective policy instruments and governance structures in place.

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Chapter 9

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Basalt columns near Vik, Iceland. By tawatchaiprakobkit

Chapter 9 | The CDR gap

A gap exists between national pledges for CDR and scenarios that meet the Paris temperature goal.

Key insights

- The CDR gap is 0.3 $GtCO_2$ in 2030, 1.2 $GtCO_2$ in 2035 and 5.2 $GtCO_2$ in 2050.
- The CDR gap is based on the difference between levels of CDR in national pledges and in scenarios that limit the end-of-century global temperature rise to 1.5°C with highest ambition.
- Current national CDR pledges sum to 2.5 $GtCO_2$ in 2030, 2.7 $GtCO_2$ in 2035 and 3.6 $GtCO_2$ in 2050. The latest NDCs submitted in 2025 did not substantively increase ambition.
- Highest Ambition scenarios have median CDR levels of 2.9 $GtCO_2$ in 2030, 3.9 $GtCO_2$ in 2035 and 8.8 $GtCO_2$ in 2050.
- If countries do not take ambitious action to reduce emissions, more CDR will be required to hold warming to 1.5°C, increasing the CDR gap in the long-term.
- Major uncertainties associated with evaluating the CDR gap remain, including ambiguities in the amount of CDR pledged by countries, the credibility of those pledges and how quickly global emissions will peak. Credibility concerns with current CDR pledges mean the CDR gap may be larger than what we assess here.

Rapid reductions in emissions from fossil fuels, land-use change and agriculture are fundamental to meeting climate goals in the coming decades. CDR will also play a key role, yet current national CDR pledges fall short of pathways consistent with 1.5°C warming; this difference is known as the "CDR gap". The most impactful development regarding the CDR gap in this version of the report (compared to *The State of CDR 2nd Edition)* is the United States' decision to leave the Paris Agreement. Disregarding the United States' net-zero target increases the gap by approximately 700 $MtCO_2$ in 2050. Otherwise, the latest round of NDCs has not delivered a step change in ambition. Urgent action is required to close the CDR gap. Without meaningful steps to reduce emissions in the next decade, the CDR gap will increase even further by 2050.

9.1 The CDR gap concept

The CDR gap is a measure of the difference between the sum of national CDR pledges and the amount of CDR in scenarios that meet the Paris temperature goal.

To calculate the CDR gap, this report estimates the amount of CDR pledged by parties to the Paris Agreement (see Chapter 5). This analysis primarily draws on the NDCs (for pledges in 2030 and 2035), and the LT-LEDSs (for pledges in 2050 and beyond) that are submitted by parties to the UNFCCC. Pledges for these three years – 2030, 2035 and 2050 – are then compared with levels of CDR in model scenarios that meet the Paris temperature goal. These scenarios are referred to as Paris-consistent scenarios, as they limit warming to below 1.5°C by the end of the 21st century (see Chapter 8).

The quantification of the CDR gap serves two functions: it highlights the amount of CDR required to reach the Paris temperature goal, and it facilitates the tracking of progress towards this goal. This allows an understanding of three broad issues: the extent to which national CDR pledges are sufficient or ambitious; whether those national pledges are achievable and, if so, at what cost; and the degree to which mitigation strategies are overly reliant on CDR at the expense of pursuing deep emissions reductions.

Key considerations when calculating and interpreting the CDR gap

Quantifying the CDR gap involves comparing national pledges against a chosen set of model scenarios that serve as benchmarks. The choice of scenarios is a normative one, as they rely on different rates of CDR scaling to balance gross emissions reductions and reach net-zero emissions. For a given temperature goal, scenarios that implement less mitigation action through reductions in GHG emissions in the near term tend to increase their dependency on CDR in the long term.[1,2] In other words, one could benchmark CDR pledges against scenarios in which ambitious mitigation is delayed, but CDR must subsequently be scaled to very high levels. In this case, the CDR gap would become larger. Conversely, one could choose to benchmark pledges against scenarios with more ambitious near-term emissions reductions but lower levels of CDR. In this case, the CDR gap would be smaller.

Our choice in this analysis is to quantify the lower bound of what the CDR gap could be. We compare the sum of parties' most ambitious CDR pledges against a set of Highest Ambition scenarios that assume immediate, ambitious action at all levels to reduce emissions (see Chapter 8). These scenarios comprehensively phase out fossil fuels and cut deforestation rates to zero while also incorporating significant efforts to reduce final energy demand through efficiency and sufficiency measures. This scenario design reduces the dependency on CDR to meet the 1.5°C temperature limit. However, because the remaining carbon budget for 1.5°C is nearly exhausted,[3] scenarios assume a degree of temperature overshoot. This means that net negative emissions will be required to return to 1.5°C towards the end of the 21st century. We interpret these scenarios as representing our current understanding of the lower bound of CDR required to meet the Paris temperature goal. It should be acknowledged, however, that this level may change. On one hand, the gap could decrease as new scenarios and literature become available. Very low energy demand or "degrowth" scenarios, for example, could involve more ambitious emissions reductions and thus achieve lower levels of CDR. Such scenarios have been published in the past but are currently out of date with respect to recent emissions trends.[4] On the other hand, the gap could increase as scenarios are updated to reflect recent trends of emissions growth.[5,6]

Box 9.1 Key terms

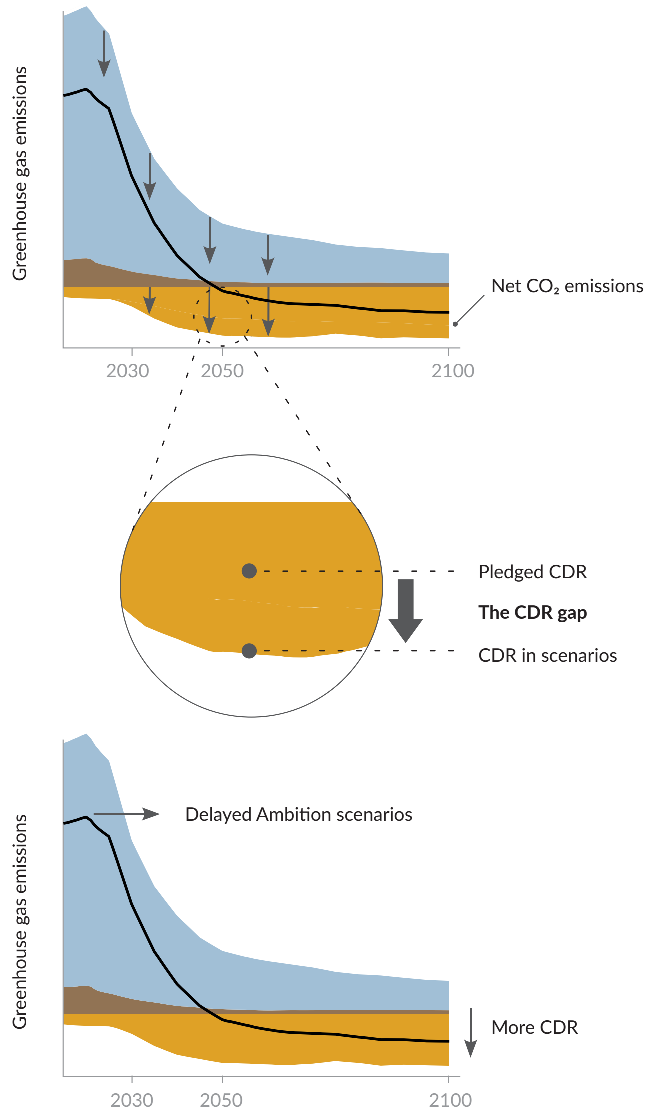
The CDR gap: measures the difference between the sum of national CDR pledges and the amount of CDR in scenarios that meet the Paris temperature goal. The gap is calculated in two benchmark years: 2030 and 2050.

NDCs: include pledges submitted by parties to the Paris Agreement detailing their climate targets and actions in the near term. NDCs submitted in 2025 contain targets for 2035, while prior NDCs have focused on 2030. As parties have by now submitted multiple NDCs, we refer to specific NDCs by their sequence (e.g. China's 2nd NDC or Brazil's 3rd NDC).

LT-LEDSs: are plans submitted by parties to the Paris Agreement detailing their long-term climate targets and actions, often describing mid-century (e.g. 2050) net-zero pledges.

National CDR pledges: outline pledged removals by parties to the Paris Agreement in 2030, 2035 and 2050, as estimated from their NDCs and LT-LEDSs. Note that parties do not pledge CDR directly, but rather net emissions reductions and/or enhanced removals and sinks. Several assumptions need to be made to estimate national CDR pledges, as described in Chapter 5. For 2030 and 2035, the NDCs of G20 countries as well as other major countries where land sinks play a key role are assessed. For all other parties, CDR is assumed to say the same.

The CDR gap concept



a) In model scenarios that reach the temperature goal of the Paris Agreement, a combination of ambitious immediate emissions reductions and a CDR scale-up are required to reduce net CO_2 emissions.

b) The CDR gap measures the difference between CDR pledged by parties, estimated from their climate targets and plans versus CDR in scenarios that assume highest possible ambition in reducing emissions. The gap is measured annually in 2030 and 2035 (against the NDCs) or in 2050 (against the LT-LEDSs).

c) If countries delay ambitious mitigation action, scenarios show that more CDR will be required to meet any given temperature goal. The CDR gap is, therefore, conditional on parties also delivering emissions reductions and will increase if they fail to do so.

Emissions: fossil CO_2 and GHG emissions
Emissions: managed land
CDR (novel and conventional)

Figure 9.1 *Illustration of the CDR gap concept showing (a) CDR in model scenarios, (b) the gap between pledged CDR and CDR in scenarios, and (c) the direction of change with more CDR in scenarios with Delayed Ambition.*

An implicit feature of the CDR gap is that countries also need to undertake emissions reductions in line with the Highest Ambition scenarios. Otherwise, the CDR requirements in the future will increase. We illustrate this by calculating how the long-term commitment to CDR increases if countries delay ambitious emissions reductions by ten years but still aim to preserve the 1.5°C temperature goal. These findings correspond to the "Delayed Ambition" scenarios outlined in this report (see Chapter 8).

The CDR gap is measured annually for years where pledged CDR values are available: 2030 and 2035 using the NDCs and 2050 using the LT-LEDSs. Despite this, it is the cumulative emissions and removals that matter for the temperature response of the climate system. In other words, what matters is the total amount of CO_2 emitted to and removed from the atmosphere during the 21st century, not the annual amount in 2030 or 2050. This is an important limitation of the analysis.

Our approach to quantifying the CDR gap in *The State of CDR 3rd Edition* differs from the 1st and 2nd Editions. In *The State of CDR 2nd Edition*, we compared national pledges against three "focus scenarios" that held warming to 1.5°C but used differing amounts of CDR.[7,8] Here, we aim to simplify the CDR gap analysis by presenting single benchmark numbers in 2030, 2035 and 2050. As in other assessments,[6] we also aim to shift towards comparing pledges against compiled scenario ranges, rather than individual scenarios that quickly become outdated relative to current trends in emissions and removals.

There are other important normative and sustainability issues to consider when evaluating the CDR gap. When appropriately implemented, certain CDR methods may come with co-benefits.[9] However, there is increasing evidence that scaling up CDR to very high levels would likely bring negative environmental, social and other sustainability impacts.[10] The scenarios used here and assessed in Chapter 8 are vetted based on their emissions trajectories. Modelling teams were asked to consider and implement sustainability limits in their model designs, for example taking account of total bioenergy use, water use and food prices. But deployment at such levels may nonetheless involve trade-offs and conflicts. Of course, any delay in ambitious mitigation action will increase the need to scaling up CDR to high levels, raising the risk that deployments will drive conflicts and inequities, for example in relation to land, energy or material resources. This, again, emphasizes the importance of rapid, ambitious reductions in near-term emissions to reduce the future dependency on CDR. Above all, the CDR gap analysis should not be interpreted as downplaying the need to reduce emissions from fossil fuels, agriculture or deforestation. At this stage, meeting the Paris Agreement climate goals requires maximal effort in all forms of climate change mitigation, whether reducing emissions or increasing removals.

Finally, it should be noted that the CDR gap considers two distinct categories of removals: conventional CDR and novel CDR (see Chapter 1). Conventional CDR refers to removals achieved through afforestation, reforestation and forest management, as well as other enhancements to the land sink via management of soils and vegetation (e.g. soil carbon sequestration in croplands and grasslands and agroforestry). A considerable amount of conventional CDR already occurs (2.2 $GtCO_2$ per year on average between 2014 and 2023) as informed by bookkeeping models, which align with values derived from NGHGIs (see Chapter 7 and its Technical Annex). The majority of pledged CDR in NDCs and LT-LEDSs is related to conventional CDR (see Chapter 5).

Novel CDR refers to methods such as DACCS, BECCS and biochar, which are in an early stage of development. Very little novel CDR takes place today, with current estimates of about 0.002 $GtCO_2$ per year in 2025 (see Chapter 7). Novel CDR is less well represented in pledges, but it is widely incorporated into scenarios – with considerable scale-up in the second half of the 21st century (see Chapter 8). We do not disaggregate pledges or scenarios into the different types of CDR here, but it should be noted that they do involve different policy challenges and other trade-offs, as discussed in other chapters of this report.

9.2 The size of the CDR gap

A significant gap remains between national CDR pledges and levels of CDR in Highest Ambition scenarios with immediate emissions reductions. National pledges are estimated to deliver 2.5 $GtCO_2$ per year of removals in 2030, which is the sum of current levels of CDR (2.2 $GtCO_2$ per year, see Chapter 7) and estimated changes in CDR from current levels to 2030 (+0.3 $GtCO_2$, see Chapter 5). The median level of CDR in the chosen scenarios reaches 2.9 $GtCO_2$ per year in 2030. This leaves a CDR gap of at least 0.3 $GtCO_2$ (see Figure 9.2).

The CDR gap

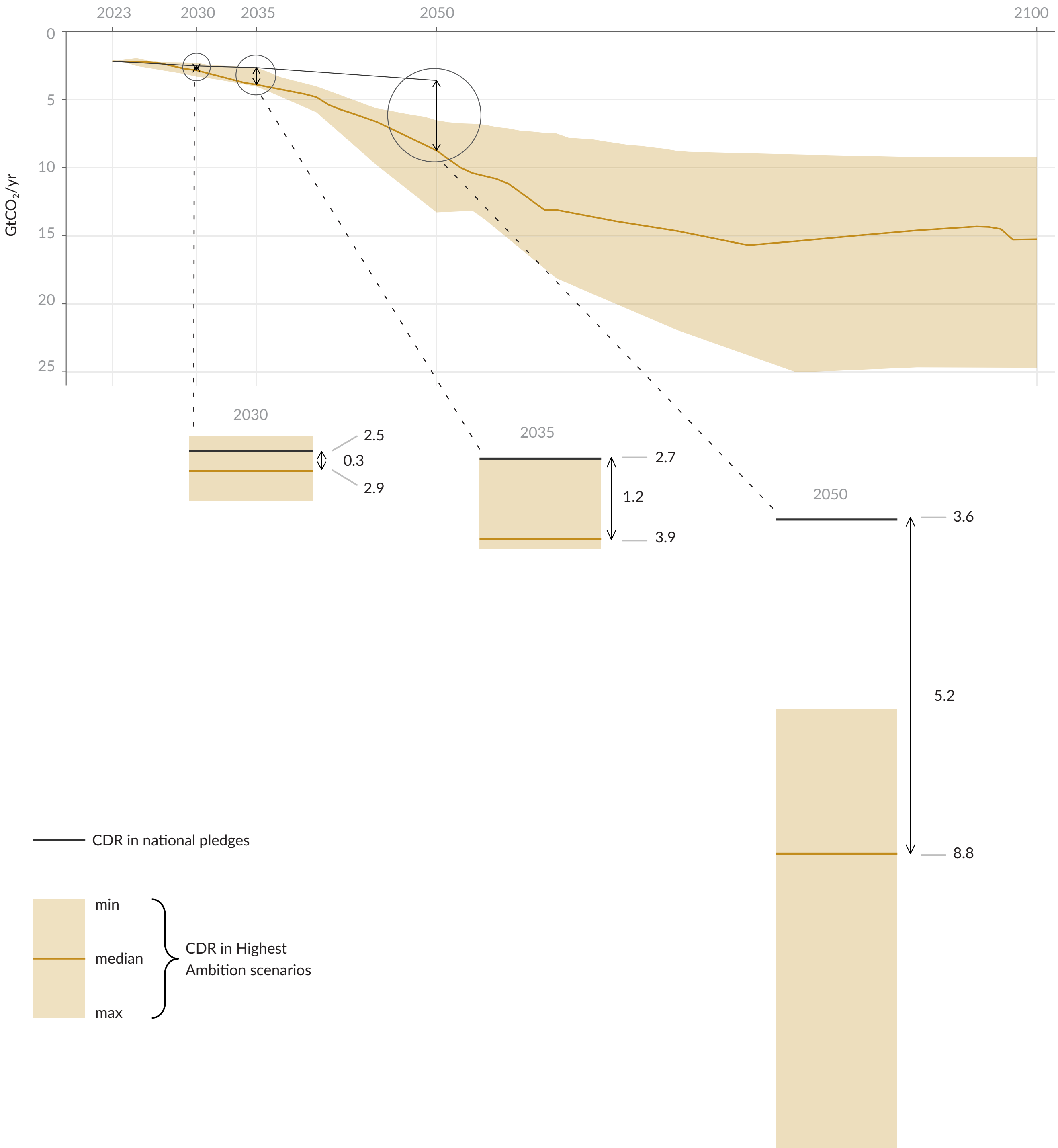


Figure 9.2 *The CDR gap in 2030, 2035 and 2050. Removals are shown here as positive numbers. CDR in national pledges refers to the most ambitious set of pledges. Least ambitious pledges – which are, for example, conditional on financing in NDCs or are from lower-bound net-zero scenarios in the LT-LEDSs – sum to 2.4 $GtCO_2$ in 2030, 2.5 $GtCO_2$ in 2035 and 3.3 $GtCO_2$ in 2050. (Note that the 2030 gap numbers do not sum perfectly due to rounding.)*

Looking ahead, the CDR gap widens to 1.2 $GtCO_2$ by 2035 and 5.2 $GtCO_2$ by 2050. These estimates are based on the most ambitious levels of CDR pledged in parties' NDCs (2.7 $GtCO_2$ in 2035) and LT-LEDSs (3.6 $GtCO_2$ in 2050), versus those in the median of scenarios with highest ambition (3.9 $GtCO_2$ and 8.8 $GtCO_2$, respectively).

The size of the CDR gap is contingent on the depth of emissions reductions that are undertaken over the coming decades. In the Highest Ambition scenarios, gross emissions are reduced by 38% in 2035 compared to levels in 2025 (see Chapter 8). In other words, global emissions have peaked, and countries are well under way to decarbonizing their energy systems, phasing out fossil fuels and halting deforestation within the next ten years. This is not the current trend in either the emissions or emission reduction pledges – both of which remain far off track for limiting warming to 1.5°C. Indeed, the CDR pledges evaluated here represent the upper bound of parties' ambitions. Benchmarking against the least ambitious CDR pledges would see the CDR gap grow by several hundred megatonnes in 2050.

A delay in ambitious emissions reductions will have long-run consequences with Delayed Ambition scenarios having to remove over 150 $GtCO_2$ more from the atmosphere by 2100 compared to the Highest Ambition scenarios. This means more effort to scale up and sustain CDR over a period of decades in the second half of the 21st century (see Table 9.1). It also means an increased reliance on novel CDR, as the potential for conventional CDR is ultimately limited by land availability. Finally, delayed emissions reductions will lead to global average temperatures exceeding 1.5°C for longer, during which time humans and ecosystems will be exposed to severe climate impacts, potentially leading to risks of reversals in land sinks, among other issues.

Consequences of delayed ambitious emissions reductions on the CDR gap

	Highest Ambition scenarios	Delayed Ambition scenarios
Cumulative CDR, 2023–2100	841 $GtCO_2$	1005 $GtCO_2$
Cumulative conventional CDR, 2023–2100	405 $GtCO_2$	398 $GtCO_2$
Cumulative novel CDR, 2023–2100	380 $GtCO_2$	577 $GtCO_2$
Years exceeding 1.5°C	55 years	68 years

Table 9.1 *Note: Median values for each category are shown.*

The CDR gap has changed in several ways since *The State of CDR 2nd Edition* was published. In terms of national CDR pledges, the most significant change has been the formal exit of the United States from the Paris Agreement in January 2026, 12 months after the start of the Trump administration. While climate action might still continue at a subnational level in the United States, the country's withdrawal from both the Paris Agreement and the UNFCCC has triggered a significant downward revision in total national CDR pledges of approximately 700 $MtCO_2$ in 2050, as we assume that the US net-zero pledge with its associated removals is no longer valid. The overall effect of the United States's withdrawal from the Paris Agreement has been evaluated as adding up to 1 $GtCO_2e$ of net emissions to current policy projections in 2030, making it a very significant factor in recent climate target and pledge assessments.[6]

Other changes to our assessment of national pledges incorporate updates relating to both methodology and historical data – not to changes in ambition levels. Since publication of *The State of CDR 2nd Edition*, none of the NDC updates from the G20 group and other large countries have included significant increases in CDR pledges, [11] and only a handful of countries have submitted new LT-LEDSs. An important methodological update for the long-term strategy (2050) estimates was to harmonize our approach with the NDC methodology: these are now calculated simply as the difference between future pledges compared to the 2014–2023 average. In previous editions we attempted to discount "indirect effects", but we no longer do so because of inherent and large uncertainties in national scale modelling of terrestrial carbon fluxes. (For a full documentation of the NDC estimates and methodology, see the Chapter 5 Technical Annex.)

9.3 Uncertainties

The precise size of the gap between CDR pledges and Paris-consistent scenarios depends, in particular, on three factors: the persistent ambiguities in national CDR pledges, credibility concerns with current pledges and uncertainties in model scenarios.

Persistent ambiguities in national CDR pledges

Identifying and calculating CDR pledges from the NDCs and LT-LEDSs is not a straightforward task due to major ambiguities in how targets and pledges are formulated and described. In general, governments provide insufficient clarity on how their historical and future committed fluxes disaggregate between additional sinks (CDR) and reduced emissions. This makes it difficult to assess both current levels of CDR activity and each government's plans for CDR.[12,13] Underlying reasons for these difficulties include an absence of mandatory requirements to disaggregate sectoral contributions to targets and pledges, issues around accuracy and consistency of reported fluxes,[14] and limited institutional capacity in developing countries.[15] Accuracy and consistency are particularly consequential for estimates of conventional CDR – which stem from pledged changes to removals in the LULUCF sector. Emissions and removals in this sector have the highest uncertainties of all GHG fluxes, and major revisions to historical data occur regularly because of new observations and modelling results.[16]

Recent developments in UNFCCC reporting, including the introduction of BTRs and updated NDCs submitted since *The State of CDR 2nd Edition*, have not reduced these ambiguities.[11] These are likely to continue and will remain a source of uncertainty for estimating the CDR gap.

As an example, the updated NDC submitted by Indonesia in 2025 provides sectoral emissions pathways that indicate how it might achieve its mitigation targets.[17] However, the historical net emissions estimate underlying the pathway for LULUCF (reported as "forestry and other land use") deviates significantly from the latest inventory data (reported as "land use, land use change and forestry") submitted less than a year prior in Indonesia's first BTR; the NDC land-use pathway starts at a historical emissions level of 221 $MtCO_2e$ in 2019, while the inventory data (CRT tables) estimates this as 819 $MtCO_2e$. The NDC notes that it uses estimates from the BTR for other sectors, but more recent data for the land-use sector. Observers, therefore, face the challenge of deciding which baseline to use for estimating future pledges, while carrying the risk that future revisions may further change the assessment.

Even among UNFCCC Annex I countries, which have long been requested to submit annual GHG inventories and have made significant investments in the measurement and tracking of land-use emissions and removals, we face issues of interpretation. For example, Japan and Canada use accounting approaches for describing their action in the LULUCF sector that renders interpretation difficult.

Credibility concerns with the implementation of national CDR pledges

When moving from policies to implementation, it is important to note that CDR methods are, or will be, implemented in existing, diverse economic sectors including energy, oil and gas, mining, forestry and agriculture. They may be facilitated by ETSs, other policy frameworks, or VCMs, with carbon removal priorities balanced against other competing societal objectives such as biodiversity protection and food production. Ensuring country-appropriate portfolios of CDR methods that are implemented and scaled up requires more than target setting alone. Countries can demonstrate credibility through actions including: establishing net-zero pledges in law; implementing CDR policies and measures; and comprehensively planning for scaling CDR. Chapter 5 includes a credibility assessment for G20 countries that reveals only a handful have transparent and credible pathways for scaling CDR.

Credibility issues with national pledges may mean that the CDR gap is actually larger than what we assess here. Most pledges for 2030 and even 2050 depend on conventional CDR to provide a majority of the removals. The LULUCF sector is highly dynamic and vulnerable to the impacts of climate change and natural influences, rendering it challenging both to quantify and to disaggregate anthropogenic from natural emissions and removals.[18,19] For example, Europe has a LULUCF target of 310 $MtCO_2e$ net removals in 2030 (53 $MtCO_2e$ more than the 2014–2023 average). Recent assessments of Europe's forest carbon sink, however, suggests that its ability to remove carbon is declining due to increasing climate impacts (e.g. pests, disease, drought and wildfires) and anthropogenic pressures (e.g. increased harvesting).[18,20,21] These types of climate change impacts are poorly captured in global Earth system models, contributing to uncertainties in the viability of future land carbon sinks.

Policymakers must account for the impacts of climate change and other human-induced pressures on LULUCF. If forests and soils are to contribute to reaching net zero, there is an urgent need to not only protect and maintain current land carbon sinks but also to limit warming as much as possible through rapid emissions cuts.[18,22,23]

Model uncertainties

One of the main sources of uncertainty in evidence from scenarios is whether they are too outdated to be accurate, especially in comparison to recent historical emissions. In previous editions of this report, the benchmarked scenarios had already been surpassed by the time of publication. Scenarios had, for example, already peaked in global emissions by 2020 and were en route to significant emissions reductions by 2030 that were far outside the range of pledges and current policy projections. As a result, Lamb et al.[7,8] applied an ex post adjustment to the scenario pathways to indicate the additional mitigation effort required to compensate for actual historical emissions. In this edition we make use of a new compilation of Highest Ambition scenarios that is far more up to date relative to historical emissions. In these scenarios, emissions follow the historical trend and do not peak before 2024 (see Chapter 8). An adjustment is therefore not applied, but it may become necessary again in future versions, depending on the state of the scenario literature and progress in net emissions reductions.

Finally, recent literature suggests that if the risk of a stronger-than-average response of the climate system to anthropogenic GHGs is factored in, governments would need to deploy several hundred gigatonnes of additional CDR in the 21st century, and/or lower their residual GHG emissions even further.[29,32] A precautionary approach therefore calls for interpreting emissions reductions and CDR levels in scenarios as the lower bound of what may be needed to safely stabilize global temperatures.

9.4 Outlook

A gap is evident between the latest national CDR pledges and scenarios consistent with the Paris temperature goal. As it stands, countries are not planning for the levels of CDR scale-up needed to compensate for historic emissions and reverse the global temperature overshoot in the second half of the 21st century. The latest round of NDCs, delivered in 2025, does not show increased ambition in terms of pledged CDR, nor have there been major developments with new net-zero pledges or LT-LEDSs. In fact, the exit of the United States from the Paris Agreement dramatically worsens the assessment for 2050. Parties need to pledge hundreds of megatonnes more CDR in 2030, over a gigatonne more in 2035, and over five gigatonnes more in 2050 to get on track for meeting the Paris Agreement temperature goals. Different approaches have been suggested for how parties can increase their ambition levels (see Box 9.2).

Box 9.2: Increasing national ambitions to close the CDR gap

Closing the CDR gap and meeting the temperature goal of the Paris Agreement requires higher collective ambition, which, in turn, means higher ambition for individual parties. While parties are mandated under the Paris Agreement to prepare and submit national mitigation targets as part of their NDCs, the treaty leaves each nation to determine for itself what a feasible and fair contribution would be. NDCs are required to meet certain standards, including that each NDC represents a progression on previous targets and reflects the parties' "highest possible ambition", meaning that governments should perform their due diligence in assessing possible mitigation options, including for CDR.[24,25] But there is no requirement that parties explicitly quantify the anticipated role of CDR in their targets and pledges, despite a broad consensus within the scientific community that such information is important for evaluating ambition and progress.[26,27]

How we judge the appropriate ambition levels for parties is inevitably a normative question, but one that has been explored by academia and civil society initiatives. In the first instance, there have been calls for parties to state transparently how CDR will contribute to their targets and pledges, limit their reliance on CDR by accelerating emissions cuts, and institute credible plans to rapidly scale up CDR.[22,28–30] Few parties have met these conditions (see Chapter 5).

Recent work has explored how parties' ambitions for scaling CDR could be informed by different "fair share" principles.[31–35] For example, if future CDR needs were allocated according to historical emissions or "carbon debt", the European Union, the United States and other industrialized countries would need to deploy a much larger share of global CDR than in pathways designed to minimize global costs.[31,33] Generally, this literature supports the notion that more developed OECD countries should be frontrunners in scaling global CDR.

The longer near-term emissions cuts are delayed, the greater the future CDR burden becomes. The sheer scale of CDR needs – even if emissions are drastically curtailed – means that what would constitute a globally equitable share of CDR deployment for many countries might not be feasible for them domestically. Financial transfers between states offer one way to reconcile the inevitable trade-offs that arise when considering what the "highest possible ambition" would be. This comes with its own challenges, such as how to ensure that CDR deployment across borders does not reproduce historical inequities in decision-making power, benefit-sharing and accountability, and that carbon flows are transparently tracked along international value chains.[36,37]

Beyond national governments, state-owned and private companies could also be considered responsible for removing CO_2. Climate justice scholars have considered how compensation from highly polluting companies could be used to fund the scale-up of expensive mitigation options like CDR.[38] For example, Kellou et al.[39] show how large, investor-owned fossil fuel companies could be considered responsible for investing in DACCS to accelerate cost reductions.

If 1.5°C is to be kept alive as a goal, some parties will need to go beyond net-zero pledges and remove more than they emit – also known as "net negative emissions" (at least in terms of CO_2, but potentially overall GHG emissions). But while a few parties have declared such intentions, none have taken steps to declare or specify net negative pledges. Establishing these and reframing national net-zero pledges as a transitional phase, not an end point, would be an important way to signal ambition in line with the Paris Agreement – particularly for those governments that could be considered to bear more responsibility.[40]

To meet their obligations and close the CDR gap, governments need to undertake an ambitious programme of planning for and delivering CDR in the coming decades. This will take time and care if we are to ensure that CDR scaling is robust, fair and durable. It is, therefore, important to start now [41] and to consider a diverse range of CDR methods to avoid over-reliance on any single approach and balance social and environmental sustainability with issues such as durability and feasibility.[23,42]

The remaining carbon budget for limiting warming to 1.5°C will likely be exhausted by 2030.[5] As we move closer to a world exceeding 1.5°C, governments still are not responding with ambitious and credible pledges to scale CDR. Reducing fossil fuel, agriculture and deforestation emissions remains a fundamental priority and precondition for stabilizing warming to avoid serious and lasting climate impacts. The next challenge, however, cannot be ignored: to ensure that we are on track for delivering on CDR at the scale needed throughout the 21st century.

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Chapter 10

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A farmer examines biochar made from rice paddy straw before its application during wheat crop sowing in Punjab.
By Aaran Patel

Chapter 10 | Costs and potentials

CDR methods vary widely in their estimated potentials, from less than 1 $GtCO_2$ per year to several tens of $GtCO_2$ per year. Removal via conventional methods is concentrated at the low-to-medium range, while some novel methods extend into the upper range. Cost estimates across all methods span a similarly wide range, from <US$10/$tCO_2$ to upper limits exceeding US$1,000/$tCO_2$. Substantial uncertainties underlie these estimates as well as the possible side effects of scaling each method.

Key insights

- Across and within CDR methods, potentials reported in the literature range widely. While some methods stand out in terms of lower (<1 $GtCO_2$ per year) or higher (tens of $GtCO_2$ per year) potentials, there is significant overlap. When considering higher-confidence estimates or more rigorous deployment assumptions, the low end of the ranges for almost all methods is near or below 1 $GtCO_2$ per year.

- Like potentials, cost estimates also range widely, with broad overlap across CDR methods. Most methods have upper limits well over US$200/$tCO_2$.

- Estimates of potentials are highly variable for many reasons, including low scientific understanding and data availability; different definitions of potentials; inconsistent assumptions about sustainability and durability; or inconsistent distinction between removals and avoided emissions.

- Cost estimates range widely for the same reasons. But other factors are also important, including different approaches within a method (e.g. there are several DACCS technologies); changing costs across level of deployment (e.g. for forestry); and different project boundaries (e.g. whether capital, operations and maintenance, or MRV costs are included and whether co-products are included in the valuation). As a result, cost estimates are often difficult to compare across methods, complicating design and policy decisions.

- Side effects can significantly shape a CDR method's removal potential and economic viability. Both positive and negative side effects are possible across all CDR methods. Importantly, side effects vary across deployment scenarios and scales.

- Limiting reliance on methods to well below their maximum potential accounts for the uncertainty in potential and preserves flexibility to implement CDR sustainably – maximizing positive side effects, limiting negative side effects and optimizing costs. This flexibility diminishes as reliance on CDR grows. Diversified portfolios of CDR methods can also help balance risks and mitigate resource constraints.

As the world remains on track to exceed the Paris Agreement's 1.5°C global warming limit – meaning that net-negative emissions will be required to reverse warming – questions arise around three dimensions of CDR:

1. How much CO_2 can be removed with each method?
2. What are the associated costs?
3. What trade-offs, risks or synergies may arise as the respective methods are rolled out?

Previous literature such as Fuss et al. (2018)[1] dates back almost a decade – a decade that has seen explosive growth in CDR knowledge[2] and the entrance of the topic into mainstream climate policy discussions.[3] In this chapter, we give an overview of the latest state of knowledge on estimated global potentials, costs and side effects of the CDR methods outlined in this report. Estimates draw on a targeted review of recent peer-reviewed research and grey literature (primarily 2018–2026, with older sources used where necessary), supplemented by expert review and input. We critically assess these heterogeneous estimates and highlight key uncertainties and knowledge gaps where evidence is limited or highly variable.

Unless otherwise indicated, potentials in this chapter are to be interpreted as technical potentials – defined, following the IPCC (2022),[4] as "constrained by biogeophysical limits as well as availability of technologies and practices. Quantification of technical potentials takes into account primarily technical considerations, but social, economic and/or environmental considerations are occasionally also included, if these represent strong barriers for the deployment of an option." Because they are based on biogeophysical limits, technical potentials are not additive, as each potential represents a resource use case maximizing the respective volumes of CDR available. Reported technical potentials for a given method may vary broadly across studies applying different assumptions on barriers to deployment. In the context of this chapter, we use "constrained" potential to indicate more rigorous assumptions on deployment conditions or higher agreement across studies. Potentials that are available at certain costs are called economic potentials.

Importantly, we do not interpret volumes of CDR deployed in scenarios of, for example, IAMs as potentials (see Chapter 8), even though these deployments also enter our assessment in comparison with the technical, bottom-up potentials. Both scenario deployments and bottom-up potentials depend on a plethora of factors such as the technological readiness level (TRL), permanence of storage and availability of resources. The treatment of these factors is not always consistent across studies; for example, estimates of the TRL for the same method may vary across different analyses. The aim of this chapter is to report estimates if they are documented in the peer-reviewed literature, along with a discussion of caveats and limitations.

Cost estimates are also heterogeneous, varying substantially depending on, for example, whether they contain capital costs or only operational costs, and whether they are assessed at the scale of a fully-mature market or a FOAK project – distinctions that are often impossible to disentangle. While detailed analyses assessing cost at scale are available for more mature technologies, many novel methods only have preliminary cost assessments.

In this chapter, we specify details about cost estimates (e.g. scope and scale) whenever possible. Ideally, a cost assessment across the different CDR methods would be based only on levelized costs of CO_2 removed (including capital and operational expenditures as well as the carbon removal efficiency), derived from LCA and techno-economic analysis to ensure comparability. However, very few such studies have been published, and those that are available review only a limited set of technologies, making a comprehensive and systematic review unproductive at this point (see Chapter 7). Where possible, we identify cost drivers and indicate whether costs are expected to increase or decrease in the future. These trends may be driven by multiple dynamics – on the one hand, increasing resource scarcities could drive up costs per unit CO_2 removed, while on the other hand, technological change, learning and economies of scale could simultaneously decrease costs.

Side effects arising from CDR deployment can affect both scalability and costs. Side effects generally refer to non-carbon outcomes of CDR deployment; these can either be positive (e.g. additional revenue streams from co-products like energy or construction materials, or ecosystem restoration that improves local microclimate or enhances habitat for endangered species) or negative (e.g. higher energy or food prices). Because the available information on side effects is too sparse for a systematic, quantitative review across methods, or across potential side effects domains,[5] we provide qualitative assessments in this chapter. We also identify this area as a significant knowledge gap that warrants further investigation, given growing demand not only from policymakers but also from buyers in the VCM, who increasingly seek information on the qualities of removal credits beyond carbon benefits (see Chapter 4). Another important aspect relevant in this context is potential competition with measures to directly reduce GHG. Significant resource bottlenecks may arise from competition among CDR methods and with other mitigation strategies, depending on scale, sustainability considerations and policy priorities.

Mitigation potentials and costs by CDR method

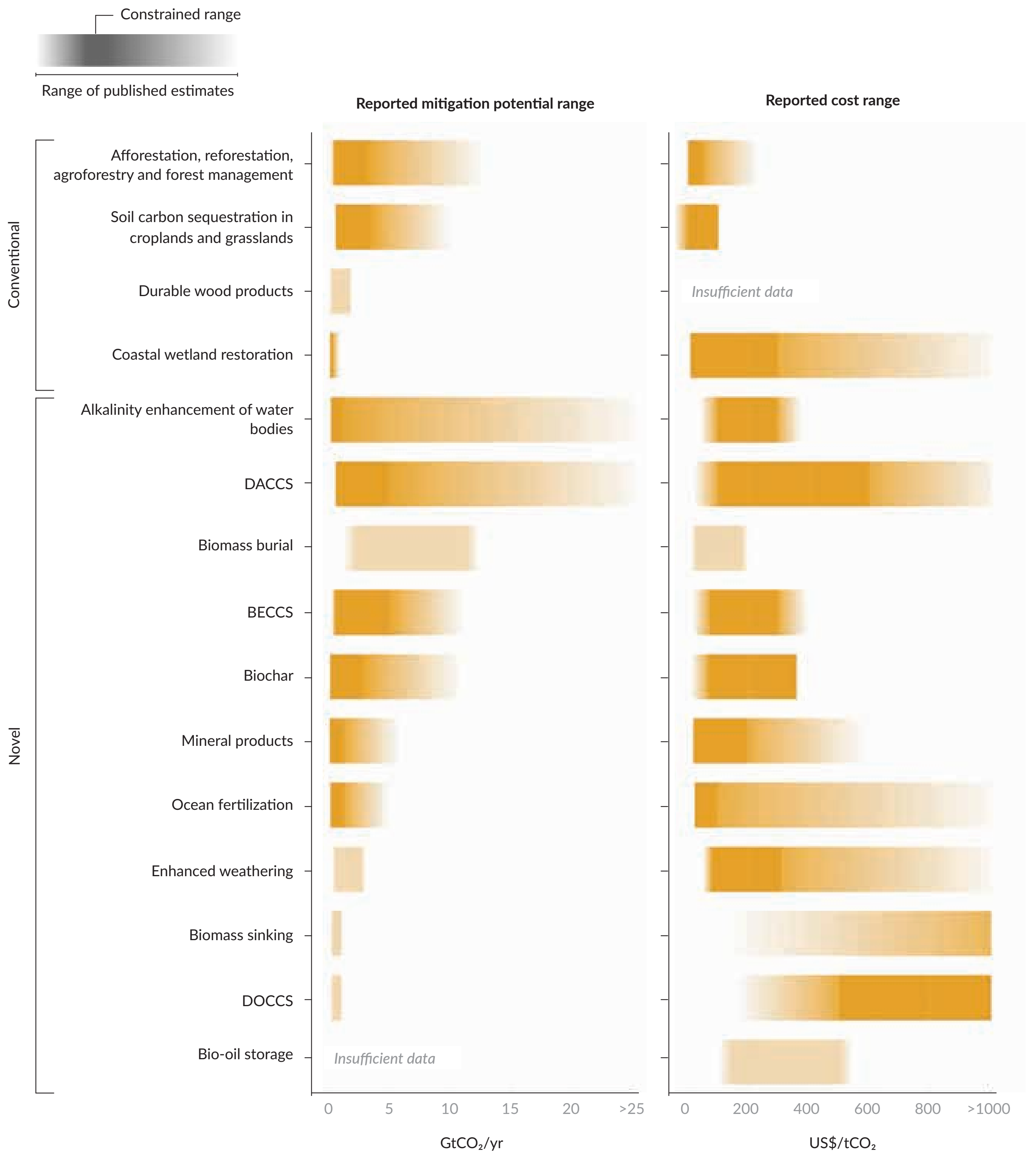

Figure 10.1 *Estimated ranges of mitigation potentials and costs of CDR methods. Presented ranges depict the spread of reported estimates in the literature. Darker shading indicates more constrained ranges, considering more rigorous deployment assumptions or higher agreement across reported estimates. Some estimates may also include avoided emissions, so we refer to mitigation potential instead of removal potential. Estimates of costs also vary across methods in terms of system scope and whether they are meant to represent current costs versus future costs at scale. For both potentials and costs, these different methodological approaches limit direct comparability across CDR methods. Further, note that estimates of potential are not additive due to overlapping resource demands and related constraints.*

10.1 CDR methods

Afforestation, reforestation, agroforestry and forest management

Afforestation, reforestation, agroforestry and forest management methods differ in implementation mode and potential side effects. They represent almost all current CDR (see Chapter 7) and are all characterized by a high level of technological readiness (TRL 8–9).[6] Nevertheless, estimates of sustainable and economic potentials vary widely: they are sensitive to the carbon price as well as uncertainties related to Earth system feedbacks.

Global potential: A rich body of literature exploring the removal potential of forest-based CDR methods has emerged in recent years. However, removal potential estimates vary substantially due to differences in the definition of forest, assumed land availability, sustainability and other constraints and feedbacks to CDR deployment.[7] The literature estimates place the technical removal potential of afforestation at up to 13 $GtCO_2$ per year.[8] Sustainable estimates – which account for unfavourable sustainability implications and Earth system feedbacks, and focus on reforestation rather than afforesting land that has historically not been covered by forest (often defined as >50 years) – suggest a considerably smaller removal potential of up to 2.2 $GtCO_2$ per year.[7,9] However, estimates of sustainable potential still vary considerably (<0.1–8.9 $GtCO_2$ per year), depending on the underlying assumptions.[7,10] In general, the assessed studies estimate CO_2 removal potential additional to current levels, which for afforestation and reforestation are approximately 2.2 $GtCO_2$ per year (see Chapter 7).

Climate-related Earth system feedbacks may emerge under warming levels above 1.5°C, possibly limiting removal potential by affecting sequestration capacity and permanence. These factors remain relatively underexplored.[11,12] The Highest Ambition scenarios (see Chapter 8) feature removals of 3.3–8.4 $GtCO_2$ per year via afforestation, reforestation and forest management by 2050, and up to 0.7 $GtCO_2$ per year via agroforestry. These scenario-based deployment rates are compatible with upper bound estimates of mitigation potential but exceed some of the more constrained estimates in the literature.

Costs: Evidence suggests removal costs at scale of around US$5–US$53 per tCO_2 removed,[1,6] while wider cost ranges (US$0–US$240/tCO_2) can be found in the literature.[13] Removal potential varies as a function of the underlying carbon price with up to 0.9 $GtCO_2$ per year at US$0/$tCO_2$ and up to 2.1 $GtCO_2$ per year at US$100/$tCO_2$ over a 30-year (non-discounted) period.[14] Note that these estimates are based on a small evidence base, narrowly focused on implementation and opportunity costs; considering additional factors, such as MRV or transaction costs, would increase the overall removal costs.[14]

Alkalinity enhancement of water bodies

There are several proposed methods for adding alkalinity to water bodies, ranging in complexity from coastal applications of enhanced weathering to electrochemical technologies. Because of the diversity of approaches, estimated TRL currently spans the complete range between fundamental research and operational deployment.[15,16] In most approaches, alkalinity is added to seawater, and the resulting uptake of atmospheric CO_2 occurs gradually over broad areas of the ocean surface, where quantification is achieved primarily through ocean modelling. Such approaches are typically referred to as ocean alkalinity enhancement (OAE). A small subset of technologies equilibrate CO_2 with alkalinity in reactors prior to discharge, facilitating MRV; these approaches use high concentrations of biogenic CO_2 from, for example, wastewater treatment plants or bioenergy facilities to facilitate faster reactions. Uncertainties remain about the efficiency of the method, with ongoing scientific study of the physical, biological and geochemical ocean processes that mediate CO_2 uptake.[17]

Global potential: The global technical potential of alkalinity enhancement is poorly constrained, estimated at <1 Gt to 100 $GtCO_2$ per year.[13,16] Potentials for specific applications in rivers or integration with existing industries (e.g. wastewater treatment plants) are estimated at 10s of $MtCO_2$ per year, and integration with the shipping industry may exceed 1 $GtCO_2$ per year.[18–20] Ocean applications have recently been considered in IAMs; in the Highest Ambition scenarios (see Chapter 8), deployment varies between <0.1 and 1.4 $GtCO_2$ per year by 2050. Economic models also anticipate slow deployment, not exceeding 1 $GtCO_2$ per year until 2100.[21] Apart from direct ocean applications, alkalinity enhancement of other water bodies has not yet been considered in IAMs.

Costs: Costs are currently estimated at US$100–US$150/tCO_2, although they may exceed US$300/$tCO_2$ for some technologies and US$600/$tCO_2$ for FOAK deployments.[16,22–24] While lower-tech options like direct placement of minerals on the seabed are estimated to be less expensive, their scientific uncertainties and MRV hurdles are higher.[1,25] Costs are expected to decrease with economies of scale, although the energy, minerals and infrastructure required may pose constraints.[26]

BECCS

BECCS is an umbrella term for a range of technologies that use biomass feedstocks for energy conversion, combined with carbon capture and geological storage. While feedstock sourcing and geological storage build on well-established practices[27] (see Box 10.1), the capture approaches occur at different levels of technological maturity. For example, bioethanol facilities with CCS are commercially deployed (TRL 9), and biomass combustion with CCS is at the demonstration stage (TRL 7), while gasification-based routes remain less mature.[28]

Global potential: Literature estimates of the global technical potential for BECCS by mid-century span 0.5–11 $GtCO_2$ per year.[13] Constrained potential, however, could be lower once sustainable biomass supply, land-use constraints and storage availability are considered. Earlier assessments suggested constrained potentials of 0.5–5 $GtCO_2$ per year by 2050.[1] A recent planetary-boundary analysis indicates a more limited sustainable potential of 0.1–0.9 $GtCO_2$ per year by mid-century from dedicated biomass plantations, assuming existing agricultural land remains reserved for food production.[29] Some additional sustainable potential may exist from agricultural and forestry residues and organic wastes, but these resource pools are region-specific and compete with other uses (see Box 10.2).

BECCS remains one of the main CDR methods deployed in IAM scenarios. In the Highest Ambition scenarios (see Chapter 8), modelled removals via BECCS reach 0.7–4.2 $GtCO_2$ per year by 2050. These scenario-based deployment levels exceed some of the lower estimates in the literature but are compatible with upper bound estimates of constrained potential.

Costs: Available cost estimates for BECCS remain sparse and divergent, reflecting the complexity of the value chain and differences in biomass feedstocks, conversion routes and system scale.[30] In addition, existing reviews often do not consistently report on the cost boundaries, for example which elements of the CCS value chain are included or whether revenues from BECCS energy products are accounted for in reported costs.

Considering this diversity of approaches, the IPCC reports a broad cost range of US$15–US$400/tCO_2,[13] while a review by Oh et al. (2025) spans US$13–US$288/tCO_2,[31] with biomass combustion routes at the upper end and bioethanol facilities at the lower end. For retrofitted bioenergy plants, modelled costs in 2030 are approximately US$140–US$260/tCO_2 for Fischer-Tropsch fuel plants, US$300–US$470/tCO_2 for energy-from-waste plants, and US$150–US$290/tCO_2 for biomass-fired power plants, where the cost estimates include forgone revenue due to the energy consumption of the CCS retrofit.[27] The IEA places current costs around US$75–US$300/tCO_2 and possible long-term costs around US$40–US$125/tCO_2.[32] While costs may fall with technological learning, limited biomass availability could also drive cost increases over time[30,31] (see also Box 10.2). This tension between learning effects and biomass constraints is also reflected in the wide range reported by the expert elicitation in Abegg et al. (2024), which focuses on biomass combustion routes and explicitly includes revenues from the energy produced, yielding estimates of US$65–US$325/tCO_2 by 2050.[30]

Biochar

While artisanal biochar production is not a novel process, readiness estimates for industrial use of biochar for carbon removal vary (TRL 7–9)[6,33] with lower readiness for biochar application cases other than soil amendment such as cement and concrete production.[27] Biochar is the largest contributor to current removals from novel CDR (see Chapter 7), and some estimates suggest high global potential; however substantial uncertainties in economic and sustainable potentials, as well as costs, remain.

Global potential: A recent review reports a wide range of estimates for biochar's technical potential, reaching up to 11 $GtCO_2$ per year.[34] But economic constraints may substantially limit deployment, with some studies suggesting an economic potential of <0.1 $GtCO_2$ per year.[34] This large range is rooted in different assessment scopes and assumptions about feedstock availability, with lower estimates when constraining feedstock sourcing to organic residues and waste materials. Recent evidence suggests a sustainable removal potential of up to 2.7 $GtCO_2$ per year, while total mitigation potential (including avoided and reduced emissions) could be up to 10.3 $GtCO_2$ per year.[34] In the Highest Ambition scenario (see Chapter 8), modelled removals from biochar reach between <0.1 and 1.1 $GtCO_2$ per year by 2050. These scenario-based deployment rates are compatible with the sustainable removal potential reported in the literature but exceed some estimates of economic potential.

Costs: A recent comprehensive cost analysis – considering biomass and biochar supply chains and pyrolysis costs as well as electricity-generation revenues – suggests future biochar costs of US$70–US$360/tCO_2,[35] while previous assessments of estimated costs by 2050 suggest lower costs of US$10–US$345/tCO_2.[1]

Biomass burial

While biomass burial is often described as readily available due to the simplicity of the proposed approach, a recent assessment suggests a TRL of 4–6.[6] The scientific literature on biomass burial is still small compared to other CDR methods.

Biomass slurry injection is a related method, wherein biomass feedstocks are injected as a slurry into deep geologic reservoirs. The technology is well-established for waste management applications and has been used for decades in the oil and gas industry.

Global potential: Several studies suggest that annual carbon removal from biomass burial could reach double-digit gigatonne levels.[36–38] Analyses of biomass slurry injection are similarly limited, with global potential estimated around 5 $GtCO_2$ per year.[39] More research is needed on both methods to assess the feasible removal potential given sustainability constraints and competing biomass uses.

Costs: Cost estimates for biomass burial at scale are on the order of US$10–200/$tCO_2$,[37,40,41] while costs for MRV would further increase overall costs. Estimates for biomass slurry injection are <US$100/$tCO_2$.[39]

Biomass sinking

Ocean biomass sinking can use either terrestrial (e.g. agricultural waste) or marine (e.g. macroalgal) biomass.[16,42,43] Each biomass type has different logistical and resource considerations, resulting in a range of estimated potentials, costs and side effects. Macroalgae cultivation is proposed in offshore locations – or in nearshore locations followed by transport of biomass to offshore locations, where it can be sunk to depths below 1,000 metres.[16,43] For terrestrial biomass, sinking is proposed in anoxic basins, either in inland water bodies or near-coastal areas, for logistical, legal and environmental reasons.[42] In addition, macroalgae sinking requires ocean modelling to verify uptake of atmospheric CO_2 into seawater, whereas terrestrial biomass captures CO_2 directly from the atmosphere (via photosynthesis on land), and does not require the same degree of ocean modelling. The TRL of both approaches is low.

Global potential: For farmed macroalgae, global CDR potential is estimated between 0.1–1 $GtCO_2$ per year.[16] Higher estimates have been put forth (e.g. up to 630 $GtCO_2$ cumulatively between 2020 and 2100); however, these derive from unrealistic simulations – with farms covering a significant fraction of the world's ocean and minimal nutrient limitation.[43] As with nutrient fertilization methods, nutrient robbing will reduce productivity in downstream ecosystems and may lower overall potential.[44,45] Uncertainties also remain about the durability of storage and impacts on ocean ecosystems, so more constrained estimates are unavailable. For sinking of terrestrial biomass, very little scholarship exists; estimates considering anoxic basin capacity propose a conceptual potential exceeding a range of 0.1–1 $GtCO_2e$ per year.[46] Realistic potential will be sharply limited by sustainable supply chains, logistics, competing biomass use and regulation.

Costs: For farmed macroalgae, production costs alone range from <US$100 to >US$10,000/tCO_2, driven by labour, transport and supplies.[47,48] Likely costs for CDR exceed US$1,000/$tCO_2$, and while economies of scale could reduce total cost to US$100/$tCO_2$, massive farms on the scale of millions of hectares would be required.[16,47,49] There are no cost estimates for terrestrial biomass sinking.

Bio-oil storage

Bio-oil storage relies on established technologies for fast pyrolysis (e.g. bio-oil production for chemicals) and underground storage (e.g. oilfield waste slurry injection), but the process of bio-oil injection for CO_2 storage is still novel and remains at an early stage of development (TRL 5).[28]

Global potential: Potentials for bio-oil storage have not yet been systematically assessed. No robust estimates of technical or constrained potential are available, and any feasible scale will depend strongly on sustainable biomass availability. Deployment in IAM scenarios remains limited: in the Highest Ambition scenario (see Chapter 8), modelled removals from bio-oil storage range from between <0.1 and 0.2 $GtCO_2$ per year by 2050.

Costs: Cost information is similarly sparse. A recent modelling study suggests that deploying many small, decentralized bio-oil facilities could achieve costs in the range of US$100–US$200/tCO_2.[50] Self-reported data of a removal company submitted to the Frontier advance market commitment (see Chapter 4) in 2024 indicated a price of around US$550/$tCO_2$.[15]

DACCS

DACCS technologies span a wide range of capture processes, each at different TRLs, while the storage component builds on well-established CO_2 geological storage practices (see Box 10.1). The most mature capture options, solid-sorbent systems and mineral looping, are already commercially deployed (TRL 9), while others remain at pilot scale, such as liquid solvent systems (TRL 6–7), or earlier development, such as electrochemical regeneration (TRL 4–6).[51] DACCS technologies are energy intensive, and performance is strongly shaped by energy demand and the carbon intensity of the energy supply.[51]

Global potential: While the literature generally treats the technical potential of DACCS as effectively unconstrained, assessments that account for limits in low-carbon energy supply and storage availability suggest more finite potential. Reported constrained estimates range from 5–40 $GtCO_2$ per year in IPCC AR6 (2022)[13] to 0.5–5 $GtCO_2$ per year by 2050 in Fuss et al. (2018).[1] Feasible CO_2 injection rates and the pace of scale-up over the coming decades could further constrain achievable annual deployment.[52]

Despite the large technical potential, IAMs often feature lower deployment levels of DACCS. In the Highest Ambition scenarios (see Chapter 8), modelled removals from DACCS range between <0.1 $GtCO_2$ per year and 1.8 $GtCO_2$ per year by 2050. Similarly, a recent systematic review by van der Spek et al. (2025) uses updated cost assumptions and finds little to no deployment across pathways remaining below 2°C or in 1.5°C pathways with limited overshoot, while higher deployment of around 3.6–9 $GtCO_2$ per year by 2100 emerges only in a 1.5°C pathway with high overshoot.[51]

Costs: The review by van der Spek et al. (2025) finds levelized costs of gross removal ranging from roughly US$400–US$2,500/tCO_2.[51] These wide ranges reflect differences in the technologies evaluated as well as the underlying assumptions used across studies, for example, regarding energy efficiency, plant configuration or solvent and sorbent choices. Many studies do not model the full DACCS value chain – notably CO_2 compression, transport and storage – and exclude additional cost components such as owner's cost or balance of plant items (i.e. the cost for supporting infrastructure). Furthermore, most studies focus on the United States, but location could also strongly influence costs. More comprehensive cost assessments are, therefore, needed. Looking ahead, the review by van der Spek et al. (2025) concludes that costs could fall to US$100–US$600/tCO_2 once deployment reaches gigatonne scale, largely through economies of scale and learning-by-doing (see Box 10.3). Variation in these projections is driven, in particular, by the assumed learning rates.

DOCCS

Most DOCCS technologies involve pumping seawater through electrochemical systems to extract dissolved CO_2. While this CO_2 extraction occurs at industrial facilities, the subsequent uptake of atmospheric CO_2 (into the CO_2-depleted seawater) occurs gradually over broad areas of the ocean surface. Current technologies are at lab-to-pilot scale (TRL 5).[16,28] Seawater mineralization is a technologically similar approach to electrochemical DOCCS, whereby seawater carbon is extracted in the form of solid carbonate minerals. The deployment, MRV and storage considerations of each method are distinct, however, and in this section we refer specifically to DOCCS.

Global potential: In theory, the technical potential of DOCCS is limited by the rate of CO_2 uptake by the ocean and geologic storage capacity, although realistic rates of seawater pumping are also likely limiting. Currently, only rough estimates of constrained potentials are available, estimated at 0.1–1 $GtCO_2$ per year, given realistic resource limits on critical metals for electrolysers and membranes, and energy demand.[16,22] Integrating DOCCS into coastal infrastructure like power plants and desalination facilities could offer the potential for approximately 50–60 $MtCO_2$ per year by 2050.[53] Given high costs, economically constrained potential remains very small (<0.1 $GtCO_2$ per year) by 2100.[21]

Costs: Although DOCCS is thermodynamically more efficient than DACCS, realistic operating conditions make the technology more expensive.[54] Estimates for the technology alone are as low as <US$100/$tCO_2$; however, systems-level costs for seawater processing raise costs to US$1,000–US$2,000/tCO_2. Co-location with existing coastal infrastructure is often considered, reducing estimated costs to US$500–US$700/tCO_2.[53,55,56] These estimates do not include MRV or CO_2 storage.

Durable wood products

The TRL is rather high for sequestration of CO_2 in long-lived wood products,[57-58] but estimates for potentials and costs at the global level are inherently uncertain, contingent on changing trajectories regarding population, average floor space per capita and climate impacts on yields.

Global potential: Bottom-up estimates vary by what type of products are included and what assumptions are made about future developments. Estimates of the contribution of wood products to storing carbon in end uses, based on historical data extrapolated along Shared Socioeconomic Pathways (see Chapter 8), show a global pool of 0.3 $GtCO_2e$ per year in 2015, rising to 0.4 $GtCO_2e$ per year by 2030 under favourable socioeconomic conditions, and up to 0.6 $GtCO_2e$ per year by 2065.[57] Different scenarios over 30 years (2020–2050) for new urban buildings designed with timber reveal potential of <0.1–2.5 $GtCO_2$ per year, depending on scenario and average floor area per capita.[58] Modelling studies based on cost-optimization estimate a cumulative potential of 23–91 $GtCO_2$ over 50 years (2015–2065)[59] or 4.1–8.1 $GtCO_2$ over 80 years (2020–2100),[60] thus featuring much higher variation than bottom-up estimates. In the Highest Ambition scenario (see

Chapter 8), modelled removals from durable wood products contribute 0.2–0.3 $GtCO_2$ per year by 2050. These scenario-based deployment rates are consistent with ranges reported in the literature.

Costs: We abstain from estimating a cost range for carbon removal through wood products on account of the vast heterogeneity of methods and the absence of comparable cost estimates in the peer-reviewed literature. Sources of uncertainty include varying project boundaries and differences in lifecycle duration. For cases where wood is replacing another material, the relative differences in costs and emissions are also important for understanding cost and economic potential.

Enhanced weathering

Enhanced weathering takes place slowly in the environment – over months to centuries depending on rock properties and environmental conditions – and MRV of CO_2 uptake remains a challenge. Consequently, assessments of TRL vary broadly, with conservative estimates of 3–4 and supplier-provided estimates of 8–9.[13,15] Silicate rocks are typically considered in both research and commercial activities, although carbonate rocks can also be effective. Most applications use agricultural land, where acidic soils expedite reaction rates, and existing supply chains can be leveraged to distribute materials.

Global potential: Estimates of global technical potential typically focus on agricultural applications and range from 0.2–2 $GtCO_2$ per year, with cumulative potential over 50 years of 25–100 $GtCO_2$.[61,62] Sustainable potential, considering biophysical and economic limits, may be limited to 0.7 $GtCO_2$ per year.[63] Higher estimates, for example reaching 95 $GtCO_2$ per year, have been proposed for use of more reactive, but less common rocks; such estimates do not consider realistic geochemical feedbacks, however, and are likely unattainable.[64] All global estimates are somewhat uncertain because of knowledge gaps in biogeochemical cycling and Earth system processes. Global estimates typically extrapolate from laboratory data, whereas actual rates in the environment are both slower and decrease over time, and significant carbon losses may occur "downstream" in soils and groundwater.[65–67] The additionality of enhanced weathering has also not yet been comprehensively assessed, considering that application of agricultural lime is already commonplace in some areas.[68] Because of the large temporal and spatial scales needed to assess enhanced weathering, confirming net CDR with real-world monitoring is challenging and requires ongoing innovations in MRV. Economically-constrained assessments often do not integrate these uncertainties and are on the high end or even exceed technical estimates, reaching 1–10 $GtCO_2$ per year by 2100.[21,35] Enhanced weathering is increasingly considered in IAMs, and the Highest Ambition scenarios (see Chapter 8) model deployment reaching <0.1–1.5 $GtCO_2$ per year by 2050.

Costs: Current cost estimates for enhanced weathering often range between US$50 and >US$300/tCO_2, although more detailed estimates from lifecycle assessments can exceed US$1,000/t$CO_2$.[27,61,64,69] Costs are dominated by transportation and the crushing and grinding of rocks. Similar to estimates of global potential, however, the net CO_2 uptake in the environment is a critical consideration, and several uncertainties have not yet been integrated into cost estimates.

Mineral products

Mineral products can store CO_2 via reaction with naturally occurring calcium- or magnesium-rich silicate rocks, or industrial by-products like cement waste, steel slag and coal ash. In most applications, mineralization technologies use concentrated CO_2 to facilitate faster reaction rates. TRL for these approaches ranges from 3–9, depending on specific feedstocks and technologies.[70] In limited applications, highly alkaline wastes or reactive feedstock synthesized from natural rocks can react directly with atmospheric CO_2 to achieve both capture and storage. There is less literature available for these passive air capture approaches. For all approaches, the long-term fate of carbonated mineral products is important for assessing both durability and additionality, especially considering potential integration with existing processes in the mining and construction sectors.

Global potential: The potential for CO_2 storage in mineral products is limited by the availability of alkaline feedstocks. While geologic reserves of mafic and ultramafic rocks are essentially unlimited, current tailings volumes could sequester <200 MtCO_2 per year.[71] Industrial wastes currently offer a potential of 1 GtCO_2 per year, increasing to 2.3–3.3 GtCO_2 per year in 2050 and up to 5.9 GtCO_2 per year by 2100.[72] However, these wastes are produced within carbon-intensive industries, for example cement, so boundary definitions are important for defining suitability for CDR. For some industrial feedstocks, resource competition may occur between other CDR methods, including enhanced weathering and alkalinity enhancement of water bodies or with mitigation activities like displacement of cement in concrete mixtures.

Costs: The cost of carbon removal via mineral products will vary with feedstock and the technology used. Current estimates range from US$10s/t$CO_2$ for highly reactive industrial wastes to >US$500/t$CO_2$ for natural feedstocks that require more chemical processing.[73] These costs often encompass the mineralization process only and do not include the cost of CO_2 capture or concentration. Recovery of valuable co-products, such as cement additives or metals, may be possible for some feedstocks, helping to defray both costs and environmental impact.[74,75] The carbon-containing products are often more expensive than conventional alternatives used in the construction industry.[76] In optimized scenarios with limited scale, integrating CO_2 mineralization with construction industries could achieve costs around US$100/t$CO_2$.[77]

Ocean fertilization

While there is medium-to-high confidence, based on several field trials, that ocean fertilization enhances primary productivity, the net effect on atmospheric CO_2 uptake remains poorly constrained, with uncertainties about the depth and extent of biomass remineralization and ultimate export to the deep sea.[78] This leads to uncertainty about both the durability of stored carbon and the efficiency of the approach. TRL is consequently low (1–2).[13,16,79] Ultimately, the net uptake of atmospheric CO_2 occurs over broad areas of the ocean surface, requiring ocean modelling for MRV.[80]

Global potential: Most estimates of the technical potential of ocean fertilization range from 0.1–1 $GtCO_2$ per year, although some exceed several $GtCO_2$ per year.[16,81] Nutrient robbing will reduce productivity in downstream ecosystems, potentially reducing the overall CDR efficiency and causing unintended negative environmental and societal impacts.[16,79] Deployment is typically proposed via ships, and the Southern Ocean is widely considered the most promising location due to its abundance of preformed nutrients, expansive size and low iron concentration.

Costs: Estimated costs are highly sensitive to the assumed export efficiency, ranging from <US$10/$tCO_2$ for high assumed efficiency to >US$10,000/$tCO_2$ for low assumed efficiency.[82,83] Capital costs are also significant, but projections of total cost are relatively insensitive to learning rates, given persistent uncertainty around export and durability.[82]

Peatland and coastal wetland restoration

Peatland and coastal wetland restoration is a wide field with many different approaches. The TRL of these approaches is usually not assessed quantitatively but is generally considered to be at a medium-to-high level. For both peatland and coastal wetland restoration, reported mitigation potentials often combine emissions reductions and removals, along with anticipated future removals; these estimates are difficult to disentangle, so isolating a CDR potential is not straightforward.

Global potential of peatland restoration: The technical potentials for reduced emissions have been estimated at about 0.5–2.5 $GtCO_2e$ per year[84] in 2030 based on the extent of degraded peatlands from the Global Peatland Database. Applying a GIS approach with IPCC emissions factors results in an estimated range of 0.3–3.4 $GtCO_2e$ per year.[85] Those estimated ranges roughly align with the IPCC assessment of 0.5–1.3 $GtCO_2e$ per year.[86] Scenario analyses[87] running up to 2100 are well within this range – at about 1 $GtCO_2$2e per year. It is important to note, however, that potential removals will be contingent on the regrowth of the peat body in the longer term. While recent literature shows that some rewetted peatlands will eventually sequester carbon, they mostly remain potential sources of mainly methane during at least the first 20 years after restoration.[88] We follow the IPCC[86] in refraining from giving explicit removal potentials and costs for peatland restoration due to lack of evidence on:

- The performance under climate change, considering that a sink can revert to a source in a warmer or drier year;
- Potential interactions with diet change and food demand; and
- Geographical differences, which are not well-studied – for example, tropical peatlands are even less well-studied with respect to carbon cycling than northern peatlands, where carbon stocks are increasingly threatened by wildfire and permafrost melt.[89]

Costs of peatland restoration: Half of the mitigation potential of 0.5–1.3 $GtCO_2e$ per year is available at up to US$100/$tCO_2$.[90] Note that costs could be very low, depending on factors such as whether co-benefits are valued. Other cost uncertainties include methods used, local conditions and complexity of projects.

Global potential of coastal wetland restoration: Macreadie et al. (2022)[91] estimate a bottom-up technical potential of 0.6–1.1 $GtCO_2e$ per year by 2030. For 2050, the most recent IPCC assessment finds a smaller range of <0.1–0.8 $GtCO_2e$ per year, based on the peer-reviewed literature, of which <0.2 $GtCO_2e$ per year would be available at a price of up to US$100/$tCO_2$ (economic potential).[92] The grey literature offers a 2050 removal potential that is only marginally higher – up to 0.8 $GtCO_2e$ per year in these categories.[93] Lower potential ranges in 2050 than in 2030 may indicate increasing scarcity.

Costs of coastal wetland restoration: Cost estimates in the grey literature are more comparable across methods than estimates from the peer-reviewed literature, where it is often unclear whether variation is due to regional differences, technology or carbon sequestration. Ranging between US$11/$tCO_2$ and US$300/$tCO_2$,[94] with mangrove restoration at the lower end and seagrass meadows at the upper end, the grey literature not only offers more narrow cost estimates for 2050, but these estimates are also two to four times lower than those found in the peer-reviewed literature.[95] These differences may stem from different lifecycle emissions, inclusion of operational and capital costs, and other factors. Generally, costs are expected to decrease by more than one-third between 2030 and 2050 due to improvements in seeding and overcoming challenges in MRV.

Soil carbon sequestration in croplands and grasslands

Soil carbon sequestration comprises a variety of management practices aimed at increasing carbon uptake and storage in croplands and grasslands through organic fertilizer use, crop management or adjusted tillage practices, among others. It is characterized by a high level of technological readiness (TRL 7–9),[6,13,96] but the potential approaches to maintain and monitor the long-term effectiveness of soil carbon sequestration remain underexplored.

Global potential: Literature estimates of the technical removal potential of soil carbon sequestration in croplands and grasslands vary substantially, with annual double-digit gigatonne removal levels on the upper end of the spectrum.[97] Several studies find substantially lower technical removal potential,[1,98] with constrained estimates ranging between 0.5 $GtCO_2$ per year[8] and 3.4 $GtCO_2$ per year.[97] Saturation effects and the risk of climate-related reversibility of soil carbon are among the critical factors constraining potential.[1,99] Such factors require further investigation to increase the robustness of potential estimates. In the Highest Ambition scenario (see Chapter 8), modelled removals from soil carbon sequestration in croplands and grasslands range from <0.1 and 0.8 $GtCO_2$ per year via by 2050. These scenario-based deployment rates are compatible with upper bound estimates of constrained potential but exceed some of the lower bound estimates in the literature.

Costs: Removal costs are highly variable depending on the underlying soil carbon management practice and due to differences in the cost factors considered (e.g. labour costs), reaching US$105 per tCO_2e on the upper end,[6] with negative cost estimates in the best case (US$-45/tCO2) when accounting for crop yield increases potentially resulting from management practices.[1]

Box 10.1 Geological storage

Geological storage of CO_2 is a requisite component of several methods at scale, including DACCS, DOCCS and BECCS. For these methods, captured CO_2 is typically injected into deep saline aquifers or depleted oil and gas reservoirs, where it is physically and chemically trapped beneath impermeable rock formations. Both the transport (via pipeline) and injection of CO_2 are well-understood based on decades of experience in EOR, and leakage risks during storage are very low.[100] Alternatively, CO_2 can also be injected into mafic rock structures where it is mineralized into solid carbonates, resulting in highly secure and permanent storage; however, this method is at an earlier stage of development.[101] While bio-oil storage also requires suitable geologic storage, structural requirements are unique from CO_2 storage, and shallower reservoirs can be used.

Storage potential: Theoretical estimates of global, geologic CO_2 storage potential are on the order of 10,000 $GtCO_2$ or more, with a majority in deep saline formations.[100,101] This capacity is approximately evenly split between onshore and offshore locations.[102] However, only a fraction of the total capacity, perhaps closer to 1,000 $GtCO_2$, is considered usable in practice, due to geological, engineering and societal constraints.[100,102,103] While this (more limited) volume remains sufficient to accommodate storage needs in most IPCC scenarios, continued reliance on fossil CCS or the large-scale deployment of CDR could deplete the resource over the next century. This raises important questions about how to allocate and prioritize storage capacity across regions, sectors and time.[102]

Costs: The cost of geological CO_2 storage involves three main components: compression, transport and storage, which typically includes MRV. Compression is required to reduce the volume of captured CO_2, allowing it to be efficiently transported and injected into deep geological formations. This step typically costs US\$10–US\$30/tCO_2, depending on target pressure and the scale of the facility.[104,105]

Transport costs vary by distance, infrastructure type and scale. For high-capacity onshore pipelines (e.g. transporting more than 1 $MtCO_2$ per year), costs are typically only a few dollars per tonne per 100 km.[101,106] Offshore pipelines are generally 40%–70% more expensive than onshore systems.[101] In certain cases, ship transport may be more cost-effective, particularly for longer distances and modest volumes. For example, transporting 1 $MtCO_2$ per year over 1,000 km by ship is estimated to cost approximately US\$20–US\$30/tCO_2.[101]

Finally, storage costs are site-specific and depend on factors such as geological conditions, injection rates, site maturity and the regulatory environment. MRV costs are often included in storage cost estimates. Onshore storage is typically less expensive, especially in already explored geological sites, with costs ranging from a few dollars to less than US\$25/tCO_2.[104,105,107] By contrast, offshore storage is generally more expensive, with estimated costs ranging from approximately US\$5–55/tCO2.[104,105] However, costs for newly developed sites remain highly uncertain and are expected to increase, reflecting increasing prices for key plant and infrastructure components and limited near-term potential for technological cost reductions.[101,108]

10.2 Wide variation in CDR potentials

Across CDR methods, a wide range of technical potentials exists, from less than 1 $GtCO_2$ per year for some methods to several tens of $GtCO_2$ per year for others (see Figure 10.1). While some methods stand out in terms of lower or higher potentials, there is significant overlap, and almost all methods have constrained potentials – which apply more rigorous assumptions or show higher agreement across studies – on the low end near (or below) 1 $GtCO_2$ per year. Because of this large spread, methods cannot be easily ranked but instead can be grouped into illustrative bins according to maximum technical potential estimates. Several methods are currently thought to offer low potentials (<1 $GtCO_2$ per year), including peatland and coastal wetland restoration, biomass sinking, DOCCS and durable wood products. Methods with low-to-medium-potentials (<1 to 5 $GtCO_2$ per year) include ocean fertilization, enhanced weathering and storage in mineral products. Several biomass-based methods, including biochar, BECCS and biomass burial, could technically offer medium potentials (up to around 10 $GtCO_2$ per year), as do soil carbon sequestration and forestry-based methods. Finally, a few methods may theoretically offer high potentials (exceeding 10s of $GtCO_2$ per year), including DACCS and OAE.

The broad ranges within and across methods result, in part, from inconsistent scopes and constraints considered in technical potential assessments. Technical potentials primarily consider biogeophysical limits but can also include social, economic or sustainability considerations if these are thought to present significant barriers to deployment.[4] There is no required level of significance to include such considerations, preventing straightforward comparison across studies. For land- and biomass-intensive methods, sustainability assumptions are particularly important and differ widely across estimates. Even for mature, conventional methods like afforestation and reforestation, potentials span several orders of magnitude, a result of variable sustainability constraints such as land availability, biodiversity, albedo and food security. Some estimates in the literature also vary significantly in scope. For example, assessments of peatland and coastal wetland restoration often include avoided emissions and implications for fluxes of non-CO_2 greenhouse gases, which are difficult to disentangle from CDR, complicating assessments of potential.

Estimated potentials also vary because of scientific uncertainty, especially for methods that leverage natural processes within the environment to capture and store carbon. For enhanced weathering, the loss of sequestered carbon through biogeochemical cycling in soils, groundwater and rivers may be a significant limit to potential; however, these processes are poorly constrained, and expert opinions differ greatly on their magnitude.[66] Similarly, estimated potentials for ocean-based methods rely on ocean models that remain under active development and which have not yet been validated for CDR conditions.[109] As another example, the net climate benefit of coastal wetland restoration – considering, for example, non-CO_2 greenhouse gases and other carbon processes – is difficult to measure and poorly constrained across locations.[110] Research into relevant, fundamental Earth system processes for these methods is ongoing.

Potentials are also dynamic, and assumptions about durability and evolving capacities are not easily reflected in static estimates. These variable temporal dynamics make static estimates of potentials difficult to compare across methods. Climate change may reduce potentials for forestry-based methods over time, for example, by slowing CO_2 uptake rates and increasing the likelihood of carbon storage reversal (i.e. lowering permanence). Along these lines, the choice of underlying scenarios is critical to informing future potentials. For example, all methods that depend on CO_2 diffusion for sequestering carbon (e.g. diffusion in plant leaves for photosynthesis) will exhibit different potentials across scenarios with different, future atmospheric CO_2 levels. Similarly, the potential of wood products depends on assumed trends about population and demand. Durability across methods is a similar concern; soil carbon sequestration and ocean biomass-based methods, for example, may only offer durability at the decadal scale, yet this is poorly reflected in estimates of potentials. Some methods may see their potential fall over time as early deployments saturate the most feasible deployment possibilities – for example, in coastal wetlands. By contrast, methods such as peatland restoration have slow uptake, or even positive emissions, before achieving full potential.

Economic potentials are only available for the subset of methods with sufficient evidence and cost data. Because economic potentials rely on technical potentials and cost estimates as inputs, they inherit uncertainties from each. Economically optimized models naturally assign higher potentials to CDR methods with lower estimated costs, often aligning economic potential with the high end of technical potential ranges. Afforestation, reforestation and forest management is a clear example, with modelled removals in IAM mitigation scenarios (see Chapter 8) reaching up to 8.4 $GtCO_2$ per year by 2050. By contrast, methods with higher estimated costs are often modelled with lower economic potential, even if environmental and sustainability constraints may be less of a concern. DACCS, for example, remains at the low Mt-scale by 2050 in many scenarios.[51]

Box 10.2 Resource competition and interaction with other mitigation options

Removal potentials drawn from bottom-up analyses are not additive across methods. CDR methods compete for resources, both among themselves and with other mitigation efforts that reduce emissions. For example, removal methods relying on geological storage compete with storage demand from industry sectors using CCS. Methods that have high energy demands compete for carbon-free energy, along with electrification efforts (see Figure 10.2). Biomass-based methods – including BECCS, biochar, biomass burial and terrestrial biomass sinking – must compete with bioenergy (without CCS) and biofuel production. For example, Minx et al. (2018)[111] show that bioenergy deployment in 2°C scenarios unfolds at similar levels over the 21st century regardless of the availability of BECCS, indicating strong demand from other sectors. Biomass may also be an important source of carbon for the chemical industry.[112] Importantly, biomass and associated resources like land and water also face demands from agriculture to feed an increasing human population as well as livestock. The multiple demands for biomass illustrate that CDR potentials need to be understood in the context of the scenario considered. For example, a low-population scenario, or one with lower meat demand, may allow for higher biomass availability for CDR. Ultimately, more research into these interacting demands is needed for a holistic assessment of potentials.

While resource constraints may lead to competition between CDR methods or with other mitigation options, some CDR methods – especially those integrated with other industries – can also generate synergies by simultaneously removing CO_2 and avoiding emissions. In the construction sector, for example, durable wood products can substitute for emissions-intensive materials such as steel and cement, and mineral product technologies can produce supplementary material byproducts that partially displace cement. In agricultural applications, both enhanced weathering and biochar (when derived from residues or organic waste) do not compete for land resources with other biomass approaches and, by contrast, can even increase biomass yields. Improved soil fertility also lowers demand for emissions-intensive synthetic fertilizers. While CDR-coupled mitigation activities are likely beneficial from a climate perspective, all such co-benefits must be carefully assessed in lifecycle analyses. CDR and emissions reductions are each managed differently across policy and market contexts, so accurately attributing the climate benefit of each activity is critical to assessing the progress of both.

Examples of competition for resources between CDR and other mitigation activities

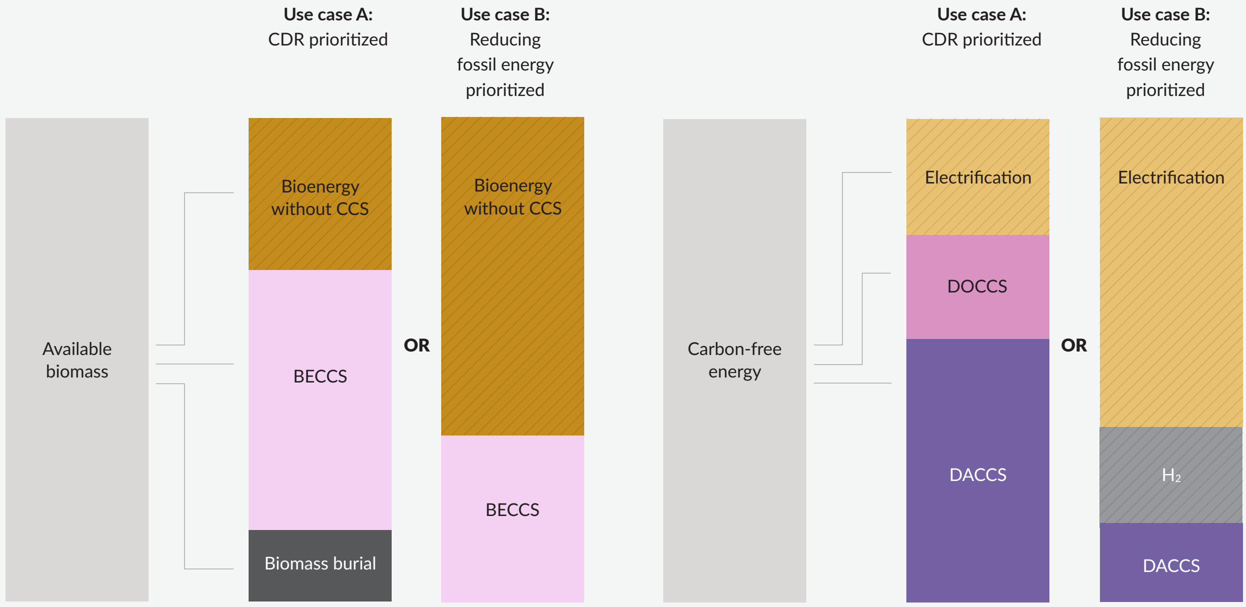

Figure 10.2 *Examples of how two limited resources may be apportioned between CDR and other mitigation activities. Hashed boxes represent non-CDR mitigation activities. For example, biomass can be used for several CDR methods, or for bioenergy without CCS. Similarly, carbon-free energy can be used for CDR pathways with high energy demands, or for activities that displace fossil energy like electrification or production of fuels like H_2. Land and water resources face similar trade-offs. Methods shown are illustrative and not comprehensive of competing approaches.*

10.3 Cost drivers and uncertainties

Cost estimates, like potentials, span wide ranges and exhibit significant overlap between methods (see Figure 10.1). For some methods, costs are relatively well-constrained below US\$100/tCO_2. Most methods, however, have broad cost windows: upper limits are well over US\$200/tCO_2, with some even exceeding US\$1,000/tCO_2. Considering variation in the types of cost presented across assessments, we group methods into illustrative bins of likely cost ranges. Forestry-based methods, soil carbon sequestration and biomass burial fall into the lowest range, with estimated costs often <US\$100/tCO_2. From a portfolio perspective, it is important to note that these CDR methods are typically associated with lower levels of permanence than methods employing geological storage, especially under ongoing climate change. Low-to-medium-cost methods – ranging from low US\$10s to several US\$100s/tCO_2 – include coastal wetlands, biochar, BECCS, mineral products and enhanced weathering. Medium-cost methods, ranging from US\$100 to US\$500/tCO_2, include alkalinity enhancement of water bodies and bio-oil storage. High-cost methods, with minimum costs ranging from several US\$100s to >US\$1,000/tCO_2, include DACCS and DOCCS. A few methods – biomass sinking and ocean fertilization – currently defy categorization due to extremely broad cost ranges, from <US$100 to >US$10,000/tCO_2. Similarly, cost estimates for durable wood products are heterogenous and currently not comparable to other methods. For most methods, current prices for CDR fall within these bottom-up cost ranges (see Chapter 4). Average prices for conventional methods fall on the low end of the cost ranges, whereas prices for novel methods are typically on the high end of (or even exceeding) their respective cost ranges. This trend is driven in part by catalytic funding to support novel methods, often in experimental deployments, but may also result from differences between FOAK costs of current deployments, versus Nth-of-a-kind (NOAK) costs represented in bottom-up analyses.

Costs are difficult to compare across methods for several reasons, including inconsistent approaches to cost analysis, variation in costs across different deployments, and scientific uncertainty. Cost analyses are often not advanced enough to distinguish current costs versus projected costs at scale or direct versus levelized costs over time. As well, they may omit information about the underlying dollar value reference year. These considerations are necessary to accurately compare estimates while simultaneously accounting for inflation. For some methods with more focused cost analyses, like DACCS, cost differentiation is possible; however, analyses for most methods do not offer this level of detail. In addition, project boundaries are not always clear in accounting considerations, for example, whether capital or operations and maintenance costs are included, whether co-benefits are included in the valuation, and whether MRV costs are considered. MRV, for example, is estimated to increase the cost of CDR by 10%–30% for most methods, although the variation in reported costs is large and some estimates exceed 50%.[15] Thus, costs presented here offer useful estimates but may not be comparable across methods. Better comparability can be expected in the future with detailed technoeconomic analyses, ideally enabling an assessment of levelized costs for all CDR methods.

Within a method, costs themselves may vary significantly because of different deployment approaches, or spatial and temporal variability. Forest restoration, for example, can be accomplished in different ways and at different costs. For resource-intensive methods like enhanced weathering, transportation distances significantly impact costs. Similarly, the distance from suitable geological formations influences the costs of methods requiring CO_2 storage. The costs of biomass-based, land-intensive methods in particular may vary across contexts, driven by differences in land opportunity costs and local wage levels. Some methods may achieve significantly lower costs by integrating with existing industries, for example DOCCS or OAE with desalination facilities to lower energy demands, and mineral storage with the construction industry to maximize co-product utilization. Costs also vary over time, which is not captured in static estimates. Highly engineered methods like DACCS expect significant cost declines with R&D and scale (see Box 10.3). Some conventional methods also expect costs to fall as MRV procedures mature; however, these same methods may also experience rising costs over time as research evolves scientific understanding or as cheaper locations are exhausted first. Thus, for many methods, the direction of cost trends remains uncertain. Considering current costs, conventional methods are more certain than novel methods but face growing uncertainty with climate change. While afforestation, for example, has been practised for a long time and its costs are relatively certain compared to more novel methods, a warmer climate could dramatically upend its cost effectiveness.

Finally, costs are also affected by scientific knowledge gaps, and uncertainty about the efficiency of some CDR methods. For novel, open-system methods – including enhanced weathering, alkalinity enhancement of water bodies, DOCCS, ocean fertilization and biomass sinking – the quantity of CO_2 durably removed per unit activity is poorly constrained, given ongoing scientific uncertainties related to Earth system processes. The few LCAs and techno-economic analyses available for these methods necessarily rely on assumptions for poorly constrained parameters. These uncertainties feed into additional costs related to MRV requirements.[15] Some conventional methods, like peatland restoration, face similar challenges resulting from possible overlap between CDR and emissions avoidance. LCA approaches to clearly delineate CDR from emissions reductions are still evolving for these methods.[113]

Box 10.3 Cost curves

Projecting future costs for CDR methods is subject to substantial uncertainty. Cost curves, which estimate cost changes over time, depend on assumptions about system boundaries, learning rates, overall system configurations (e.g. cost structure and merit order of the energy system) and regulatory frameworks.[27] Although learning curves are widely used to project future cost reductions, their application to CDR is challenging. They typically rely on historical cost and deployment data to establish a baseline for future learning, which is limited for CDR methods that remain at an early stage of development. They also assume smooth cost reductions as deployment increases, whereas actual cost trajectories may be uneven due to technological, policy or market developments. In addition, learning curves implicitly require a predictable long-run demand trajectory, which does not yet exist for CDR.[27] As a result, cost projections for CDR should be interpreted as indicative rather than predictive. We discuss examples for DACCS and BECCS to illustrate a range of potential cost changes over time.

Several studies have assessed the costs of FOAK and NOAK for DACCS plants, summarized in van der Spek et al. (2025).[51] FOAK plants face high capital costs, limited design optimization and a lack of operational experience, whereas NOAK plants benefit from technological learning and economies of scale. As a result, all DACCS technologies are expected to see significant cost reductions when moving from FOAK to NOAK, though the magnitude varies across technology types. The projections shown in Figure 10.3 depend on assumed capital expenditure (CAPEX) and operational expenditure (OPEX) learning rates, where OPEX learning rates remain especially uncertain given limited current deployment.

Future BECCS costs are shaped not only by technological learning but also by upstream and downstream factors such as feedstock prices and energy market conditions. While modelling studies often apply learning curves to BECCS capital costs, leading to projected cost reductions similar to DACCS,[27] recent expert elicitation shows divergent expectations. Some experts foresee this fall in costs associated with operational improvements; however, others anticipate rising costs driven by increasing feedstock prices and competition for waste materials.[30] Several experts also emphasize that uncertainty widens over time as multiple cost drivers evolve simultaneously, preventing even directional projections of cost evolution.

Published cost trajectories for DACCS technologies

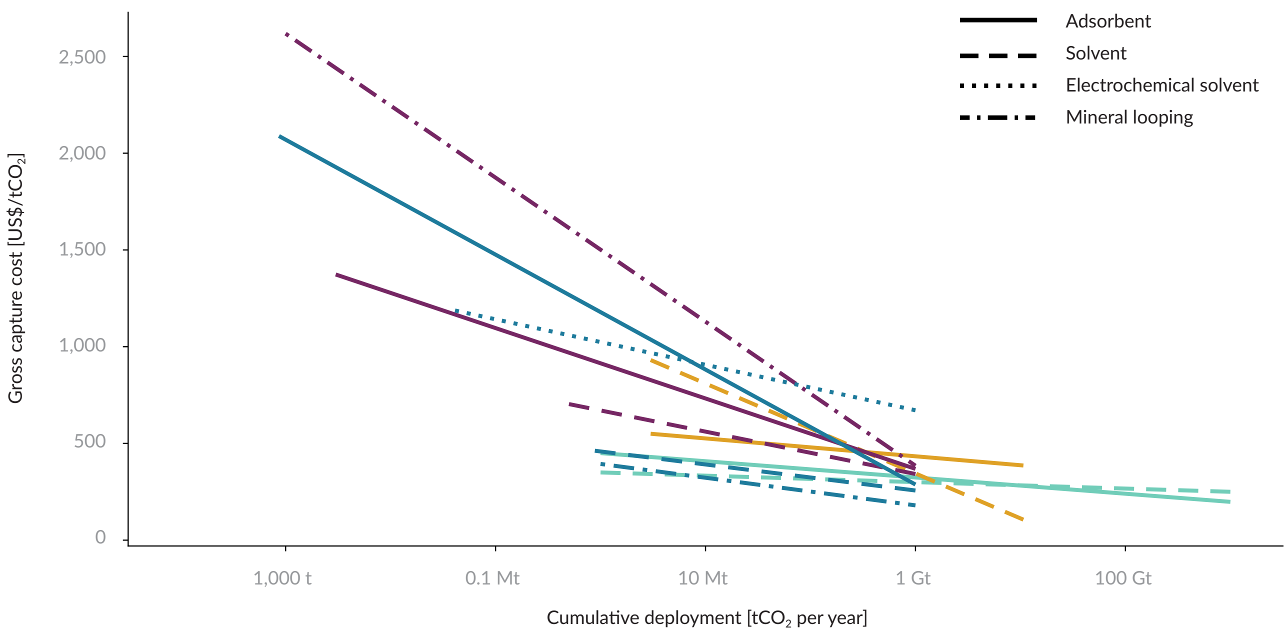

Figure 10.3 *Cost trajectories for DACCS technologies from different studies, harmonized to 2024 levelized cost of gross CO_2 captured. Not all estimates include the cost of CO_2 transport and storage. Figure adapted with permission (CC-BY) from van der Spek et al. (2025); line colors represent individual studies as cited in the original.*[51]

10.4 Consideration of side effects

Side effects refer to any deployment impact other than removing CO_2 from the atmosphere.[5] Side effects – both positive and negative – can significantly shape the scalable potential and economic viability of CDR. They influence where, how, how much and at what cost removal can occur sustainably. Specific side effects and their relative magnitude vary not only across methods but also across implementation modes and deployment contexts. For example, the sustainability of forest-based CDR depends on the suitability of land allocated for deployment; impacts on biodiversity or food production can be either positive or negative, depending on the deployment context.

Many possible negative side effects arise from extensive resource demands and resulting competition with other activities, including land, biomass, water, minerals and energy. Methods that require dedicated land use (e.g. forestry methods, durable wood products, and peatland and coastal wetland restoration) must balance CDR against other priorities. For example, competition with agriculture may lead to conflict about farmers' incomes or food security, thus limiting scalability.[84,114] However, new research also shows that, for example, cultivating crops on wet or rewetted peatlands can lessen economic and ecological trade-offs.[115] For forestry methods – next to the biogeophysical effects that may result from changes in temperature, precipitation, downstream water availability and flood mitigation[116] – there may also be competition with ecosystem conservation.[59,60,117] Biomass-based methods – including BECCS, biochar, bio-oil storage, biomass burial and sinking of terrestrial biomass – face similar challenges related to land-use prioritization and sustainable biomass sourcing.[4] Land-use conflict or competition for biomass (see Box 10.2) could lead to unsustainable sourcing and agricultural expansion, undermining climate benefits through increased fertilizer and water use, land-use change emissions, non-CO_2 GHG emissions and decreased albedo.[29,118] For methods requiring mineral feedstock – including enhanced weathering, mineral products and most alkalinity enhancement applications – expansion of mining also poses environmental concerns, unless waste products can be productively used. Finally, competition for energy with other mitigation activities is particularly challenging for energy-intensive methods like DACCS, DOCCS, some alkalinity enhancement methods and certain mineral storage methods. For example, deployment of DACCS at the one-gigatonne scale could increase global energy demand by around 5%–6%.[51] Across CDR methods, negative impacts related to resource use can be limited for well-designed deployments at limited scales. However, minimizing these side effects becomes more challenging as CDR scales.

Negative side effects may also arise from ecosystem impacts, especially for open-system methods distributed across the land or ocean. Land-based methods, including soil carbon sequestration and those using biomass, may affect water or nutrient cycling at scale.[5] Similarly, enhanced weathering could result in trace metal contamination of soil if feedstocks are not carefully monitored. For ocean-based methods, potential impacts on ocean ecology are a primary concern. Ocean fertilization and sinking of marine biomass must resolve concerns related to nutrient robbing, changes to ecological structure and deep ocean deoxygenation.[16,43,119] Nutrient robbing is of particular concern, as it may reduce the net CDR efficiency and amplify climate stressors on marine biota.[79] OAE and DOCCS may have different impacts on marine species, although these are expected to be more localized.[120,121]

At the same time, certain methods can yield positive impacts, or co-benefits, if carefully implemented. Reforestation, and peatland and coastal wetland restoration can provide multiple ecosystem services and support increased biodiversity, especially when using native and diverse plant species in places and where the historic land cover is compatible with a targeted intervention – such as reforestation in degraded ecosystems that were historically forest lands. Some methods can mitigate climate-related risks, making them valuable components of ambitious mitigation portfolios; for example, peatland and coastal wetland restoration may prevent flooding, reduce erosion and – in the case of peatlands – mitigate fire risk.[84,122] Soil-based methods like soil carbon sequestration, enhanced weathering and biochar can improve soil health, enhance crop productivity and reduce emissions of non-CO_2 greenhouse gases.[5] These methods may also offer indirect climate benefits by reducing fertilizer use. Such benefits are important for contextualizing CDR within broader environmental objectives and considering achievable potential deployment.

Ultimately, limiting reliance on CDR methods to well below their maximum potentials preserves flexibility to implement CDR sustainably, maximizing positive side effects and limiting negative side effects. This flexibility diminishes as reliance on CDR grows. Diversified portfolios of CDR methods also help balance potential trade-offs.

Box 10.4 Limitations and knowledge gaps

Knowledge gaps exist across methods, impacting estimates of both CDR potentials and costs. These gaps arise from unique challenges within each method (e.g. scientific uncertainties) as well as from systematic inconsistencies in scope and lifecycle accounting that span methods. While there has been much progress in recent years to reduce uncertainty across methods, assessments still necessarily rely on many assumptions and expert opinions to navigate remaining knowledge gaps. Improved harmonization across assessments and coordinated scientific effort targeting major uncertainties will help fill these gaps and increase confidence in CDR potentials and cost ranges. We list here the most important knowledge gaps distilled from this chapter's assessment:

- Different assessment methods and assumptions about sustainability, project boundaries, lifecycle duration and future trends (e.g. alternative biomass demands) contribute to uncertainties for both potentials and costs. Accurate comparisons will require more harmonized approaches.
- Across methods, MRV protocols are at early stages, and costs remain unclear. Comparable data on MRV costs are lacking, with only one reference, mainly based on developer estimates.[15] While the importance of this (often overlooked) cost component is recognized, there is a pressing need for more rigorous quantitative comparisons.
- Cost estimates for several CDR methods draw upon a small evidence base, narrowly focused on implementation and opportunity costs and with limited project boundaries. Comprehensive LCA is needed across technologies to enable consistent cost comparisons across methods. Future research should also engage in systematically analysing the sensitivity to different factors to better understand uncertainties, priorities in resolving them and implications for deployment strategies over time. In addition, some cost items are probably underestimated/neglected, such as those referring to insurance and finance. These and other costs may also vary geographically.
- Quantitative and comparable information on potential side effects remains scarce. The mode of implementation, local deployment context, deployment scale and counterfactual impacts of non-deployment are critical considerations when assessing the potential impact of both positive and negative side effects. As a next step, a systematic evaluation of the different approaches to estimating potentials, which was beyond the scope of this chapter, would be needed.
- For many open-system methods that capture or store carbon across broad areas in the terrestrial environment (e.g. peatland and wetland restoration, soil carbon sequestration and enhanced weathering), ongoing scientific questions contribute to uncertainty in CDR potentials. These include, for example, poorly understood impacts on biogeochemical cycling, non-CO_2 GHGs and Earth system processes that impact both carbon storage and scalability. Similarly, ocean-based methods face uncertainty related to impacts on marine ecology and biogeochemistry, as well as challenging MRV. Marine biomass-based methods (ocean fertilization and macroalgae sinking) must assess the impact of downstream nutrient robbing. All marine CDR methods, including OAE and DOCCS, must develop methods to accurately quantify atmospheric CO_2 uptake.

10.5 Outlook

Technical potentials range widely – both across and within CDR methods – from less than 1 $GtCO_2$ per year for some methods to several tens of $GtCO_2$ per year for others. Cost estimates also span wide ranges, from well below US$100/$tCO_2$ to over US$1,000/$tCO_2$. These results, based primarily on peer-reviewed literature, are broadly consistent with other recent CDR cost assessments, such as the recent CO_2RE report.[27] Accurately estimating potentials is difficult for many reasons, including low scientific understanding and data availability, different definitions of potential, inconsistent assumptions about sustainability and durability, or inconsistent distinction between removals and avoided emissions. While these factors also translate into uncertain cost estimates, uncertainty is further exacerbated by variable costs for different approaches within a method (e.g. restoration can be accomplished in different ways, biochar may use different feedstocks) and by different project boundaries. Costs may turn out to be much higher when capital, operations and maintenance, and MRV expenditures are all included. By contrast, some costs may turn out to be lower when co-benefits and co-products are included in the valuation. Because of these variations and uncertainties, a cross-method comparison of estimates for either costs or potentials is challenging. Side effects can significantly shape a CDR method's scalable potential and economic viability, but a consistent assessment is difficult here, as well, because side effects vary across deployment scenarios and scale. Limiting reliance on CDR methods to well below their maximum potentials preserves flexibility to implement CDR in ways that are environmentally responsible and socioeconomically sustainable. Diversified portfolios of CDR methods also help balance trade-offs.

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Chapter 7

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Glossary

Additionality: the extent to which emission reductions or removals would have occurred in the absence of the associated policy intervention or activity. An additionality test is applied in carbon credit programs to ensure that credits are not awarded for mitigation that would have occurred in the absence of the carbon credit revenue.

Afforestation: Conversion to forest of land that was previously not forest.

Agroforestry: Growing trees on agricultural land while maintaining agricultural production.

Alkalinity enhancement of water bodies: Addition of alkaline minerals or their dissociation products to water bodies such as the ocean, rivers or lakes. This increases surface total alkalinity and may thus increase carbon dioxide (CO_2) uptake.

Biochar: Relatively stable, carbon-rich material produced by heating biomass in an oxygen-limited environment. Assumed to be applied as a soil amendment unless otherwise stated.

Bioenergy with Carbon Capture and Storage (BECCS): Process by which biogenic CO_2 is captured from a bioenergy facility (producing power, heat, hydrogen, liquid fuels or gas), with subsequent geological storage.

Biomass burial: Burial of biomass in land sites such as soils or disused coal mines. Excludes storage in the typical geological formations associated with CCS.

Biomass sinking: Sinking of terrestrial (e.g. straw) or marine (e.g. macroalgae) biomass in the marine environment. To count as CDR, the biomass must reach the deep ocean where the carbon has the potential to be sequestered durably.

Bio-oil storage: Oil made by biomass conversion and placed into geological storage.

Carbon credit: A tradeable certificate representing one tonne of CO_2 or carbon dioxide equivalent (CO_2e) avoided, reduced or removed.

Note 1: The majority of carbon credits currently traded are emissions reduction credits.

Note 2: Carbon credits are commonly purchased to offset the greenhouse gas (GHG) emissions of the purchasing entity. An entity can also choose to retire a carbon credit without using it as an offset.

Carbon Capture and Storage (CCS): A process in which CO_2 is captured, conditioned, compressed and transported to geological storage. This term is commonly applied in the context of fossil CO_2. To count as CDR, however, captured CO_2 must come from the atmosphere, either directly from ambient air (see DACCS) or via biomass (see BECCS) or seawater (see DOCCS).

Carbon Capture and Utilisation (CCU): A process in which CO_2 is captured and used in the manufacture of products. Capture of atmospheric CO_2 for the manufacture of durable products such as concrete or timber for construction is classified as CDR. Use of atmospheric CO_2 in the manufacture of products that do not store carbon durably (before releasing it back into the atmosphere), such as carbonated drinks or fuels, is not CDR. Use of fossil CO_2 in the manufacture of products is also not CDR.

Carbon Dioxide Removal (CDR): Human activity capturing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes enhancement of biological or chemical CO_2 sinks, but excludes natural CO_2 uptake not directly caused by human activities.

Conventional CDR: CDR methods that are well established, already deployed at scale and widely reported by countries as part of land use, land-use change and forestry (LULUCF) activities. The methods included in this group are afforestation, reforestation and forest management; agroforestry; soil carbon sequestration in croplands and grasslands; peatland and coastal wetland restoration; and durable wood products.

Direct Air Capture (DAC): Chemical process by which CO_2 is captured directly from the ambient air. Captured CO_2 can be stored geologically (see DACCS), or used in products (see CCU).

Direct Air Carbon Capture and Storage (DACCS): Chemical process by which CO_2 is captured directly from the ambient air, with subsequent geological storage.

Direct Ocean Carbon Capture and Storage (DOCCS): Chemical process by which CO_2 is captured directly from seawater, with subsequent geological storage. To count as CDR, this capture must lead to increased ocean CO_2 uptake.

Durability: The capacity to store carbon over time without releasing it back to the atmosphere. In this report, carbon pools with characteristic storage timescales on the order of decades or more are classed as sufficiently durable for CDR. These include trees, wetlands, soils, biochar, durable wood products (e.g. timber for construction), solid carbonate minerals, marine sediments, ocean bicarbonate, depleted fossil fuel reservoirs, saline aquifers and mineral rock formations.

Durable wood products: Wood products which meet a given threshold of durability, typically used in construction. These can include sawnwood, wood panels and composite beams, but exclude less durable products such as paper.

Enhanced oil recovery (EOR): Additional production of oil after primary (e.g. pumping) and secondary (e.g. water injection) recovery. EOR can use various approaches, one of which is injection of CO_2 into the oil field.

Enhanced weathering: Increasing the natural rate of removal of CO_2 from the atmosphere using silicate and carbonate rocks, either by spreading them over soil or beaches, or by processing them in situ (e.g. at mine tailings).

Forest management: Stewardship and use of existing forests. To count as CDR, forest management practices must enhance the long-term average carbon stock in the forest system.

Mineral products: Production of solid carbonate materials for use in products such as aggregates, asphalt, cement and concrete, using CO_2 captured from the atmosphere. This includes biogenic CO_2 from BECCS or biochar, if applied this way.

Monitoring, Reporting & Verification; or Measurement, Reporting and Verification (MRV): Procedures for quantification, documentation and independent review of reported emissions and removals, in the context of national inventory reporting, emissions trading and voluntary claims such as carbon neutrality or net zero emissions.

Novel CDR: CDR methods that generally have a longer characteristic storage timescale and lower level of readiness for deployment and are therefore currently deployed at smaller scales. Such methods include Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Carbon Capture and Storage (DACCS), enhanced weathering, biochar soil amendment, mineral products, biomass burial, Direct Ocean Carbon Capture and Storage (DOCCS) and alkalinity enhancement of water bodies.

Ocean fertilisation: Enhancement of nutrient supply to the near-surface ocean with the aim of sequestering additional CO_2 from the atmosphere stimulated through biological production. Methods include direct addition of micro-nutrients or macro-nutrients. To count as CDR, the biomass must reach the deep ocean where the carbon has the potential to be sequestered durably.

Offset (noun): A unit that represents the reduction, avoidance or removal of a tonne of CO_2 or CO_2e by one entity, commonly purchased as a carbon credit, that is used by another entity to counterbalance a tonne of GHG emissions by that other entity.

Offset (verb): To counterbalance a quantity of GHG emissions by retiring or canceling an equivalent quantity of carbon credits.

Note: GHG emissions of an entity can also be counterbalanced through CDR undertaken by that entity.

Overshoot pathway: Pathway that first exceeds a specified global warming level (e.g. 1.5°C) and then returns to or below that level again before the end of a specified period of time (e.g. before 2100).

Paris temperature goal: The long-term temperature goal as set in Article 2 of the Paris Agreement (i.e. "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels").

Peatland and coastal wetland restoration: Assisted recovery of inland ecosystems that are permanently or seasonally flooded or saturated by water (such as peatlands) and of coastal ecosystems (such as tidal marshes, mangroves and seagrass meadows). To count as CDR, this recovery must lead to a durable increase in the carbon content of these systems.

Reforestation: Conversion to forest of land that was previously deforested.

Residual emissions: Remaining gross emissions when net-zero, and subsequently net-negative, emissions are reached. Can apply to both net zero CO_2 and net zero GHG emissions, from local to global scales and at company or sector level. To reach net-zero emissions, the amount of CDR must equal the amount of residual emissions over a given period. To reach net-negative emissions, the amount of CDR must exceed residual emissions.

Soil carbon sequestration in croplands and grasslands: Land management changes in croplands and grasslands that increase the soil organic carbon content.

Abbreviations

A$	Australian dollar
ACCU	Australian Carbon Credit Unit
AFOLU	agriculture, forestry and other land use
AR6	Sixth Assessment Report of the Intergovernmental Panel on Climate Change
BECCS	bioenergy with carbon capture and storage
BTR	biennial transparency report
$CaCO_3$	calcite
CAGR	compound annual growth rate
Can$	Canadian dollar
CAP	Common Agricultural Policy of the European Union
CAPEX	capital expenditure
CCER	China Certified Emission Reduction
CCS	carbon capture and storage
CCU	carbon capture and utilization
CCU/S	carbon capture and utilization/storage
CDM	Clean Development Mechanism
CDR	carbon dioxide removal
CER	certified emission reduction
CH_4	methane
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
COP	Conference of the Parties
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CPDB	Climate Policy Database
CRC	carbon removal credit
CRCF	Carbon Removals and Carbon Farming Regulation
DAC	direct air capture
DACCS	direct air carbon capture and storage
DEI+	Demonstration Energy and Climate Innovation
DIC	dissolved inorganic carbon
Dkr	Danish krone
DOCCS	direct ocean carbon capture and storage
EDGAR	Emissions Database for Global Atmospheric Research
EJ	exajoule
EOR	enhanced oil recovery
EPO	European Patent Office
ETS	emissions trading system
€	euro

EU	European Union
EU ETS	European Union Emissions Trading System
EW	enhanced weathering
F-gases	fluorinated greenhouse gases
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	Food and Agriculture Organization Statistics
FEED	front-end engineering and design
FOAK	first-of-a-kind
GCAM	Global Change Analysis Model
GCOM	Greenhouse Gas Crediting and Offsetting Mechanism
GDP	gross domestic product
GHG	greenhouse gas
Gt	gigatonne
ha	hectare
HWP	harvested wood product
IAM	integrated assessment model
ICAP	International Carbon Action Partnership
ICVM	Integrity Council for the Voluntary Carbon Market
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ITMO	Internationally Transferred Mitigation Outcome
JCM	Joint Crediting Mechanism
JI	Joint Implementation
km	kilometre
kt	kilotonne
LCA	lifecycle assessment
LT-LEDS	Long-term Low Emission Development Strategy
LTR	level of technological readiness
LTS	long-term strategy
LULUCF	land use, land-use change and forestry
Mha	million hectare
MRV	measurement, reporting and verification; monitoring, reporting and verification
Mt	megatonne
N_2O	nitrous oxide
NDC	nationally determined contribution
NECCS	Negative Emissions Carbon Capture and Storage Fund
NEDO	New Energy and Industrial Technology Development Organization
NGHGI	national greenhouse gas inventory
NGO	non-governmental organization
NKr	Norwegian krone
NOAK	nth-of-a-kind
NZI	Net Zero Insights

OAE	ocean alkalinity enhancement
OECD	Organisation for Economic Co-operation and Development
OPEX	operational expenditure
PACM	Paris Agreement Crediting Mechanism
PATSAT	European Patent Office Worldwide Patent Statistical Database
PV	photovoltaic
£	pound sterling (British)
R&D	research and development
RD&D	research, development and demonstration
REDD+	reducing emissions from deforestation and forest degradation in developing countries
SBTi	Science Based Targets initiative
SCS	soil carbon sequestration
SDE++	Stimulation of Sustainable Energy Production and Climate Transition
SDG	Sustainable Development Goal
SFLC	single factor learning curve
SKr	Swedish krona
SRM	solar radiation modification
t	tonne
TEA	techno-economic assessment
TRL	technology readiness level
UK	United Kingdom
UK ETS	United Kingdom Emissions Trading Scheme
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
US$	United States dollar
VCM	voluntary carbon market


THE STATE OF
Carbon
Dioxide
Removal