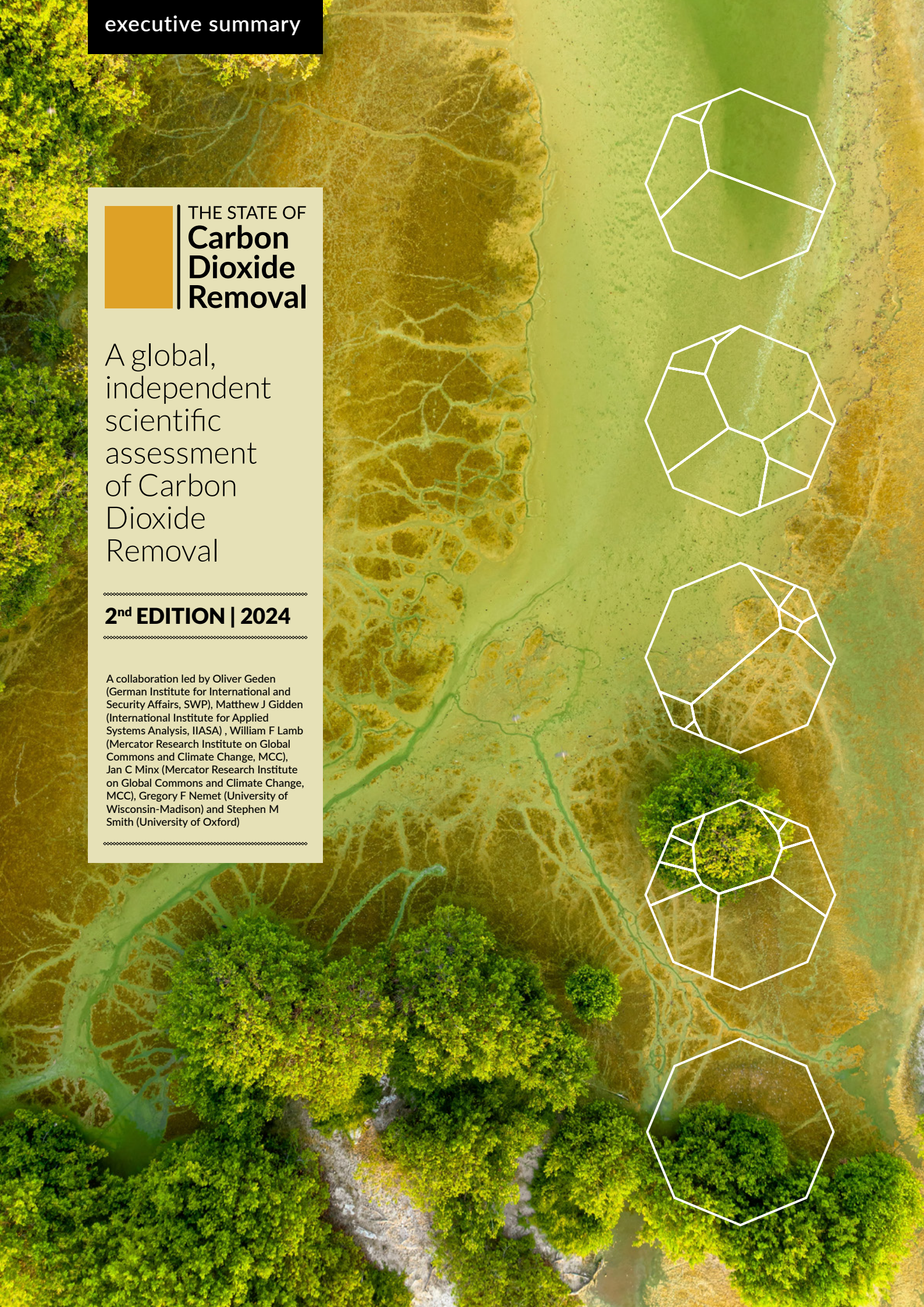
executive summary

# THE STATE OF Carbon Dioxide Removal

A global, independent scientific assessment of Carbon Dioxide Removal

**2nd EDITION | 2024**

A collaboration led by Oliver Geden (German Institute for International and Security Affairs, SWP), Matthew J Gidden (International Institute for Applied Systems Analysis, IIASA) , William F Lamb (Mercator Research Institute on Global Commons and Climate Change, MCC), Jan C Minx (Mercator Research Institute on Global Commons and Climate Change, MCC), Gregory F Nemet (University of Wisconsin-Madison) and Stephen M Smith (University of Oxford)



# Executive summary

## 1. Meeting the Paris Agreement's long-term temperature goal requires rapid greenhouse gas emission reductions and near-term scale-up of carbon dioxide removal (CDR).

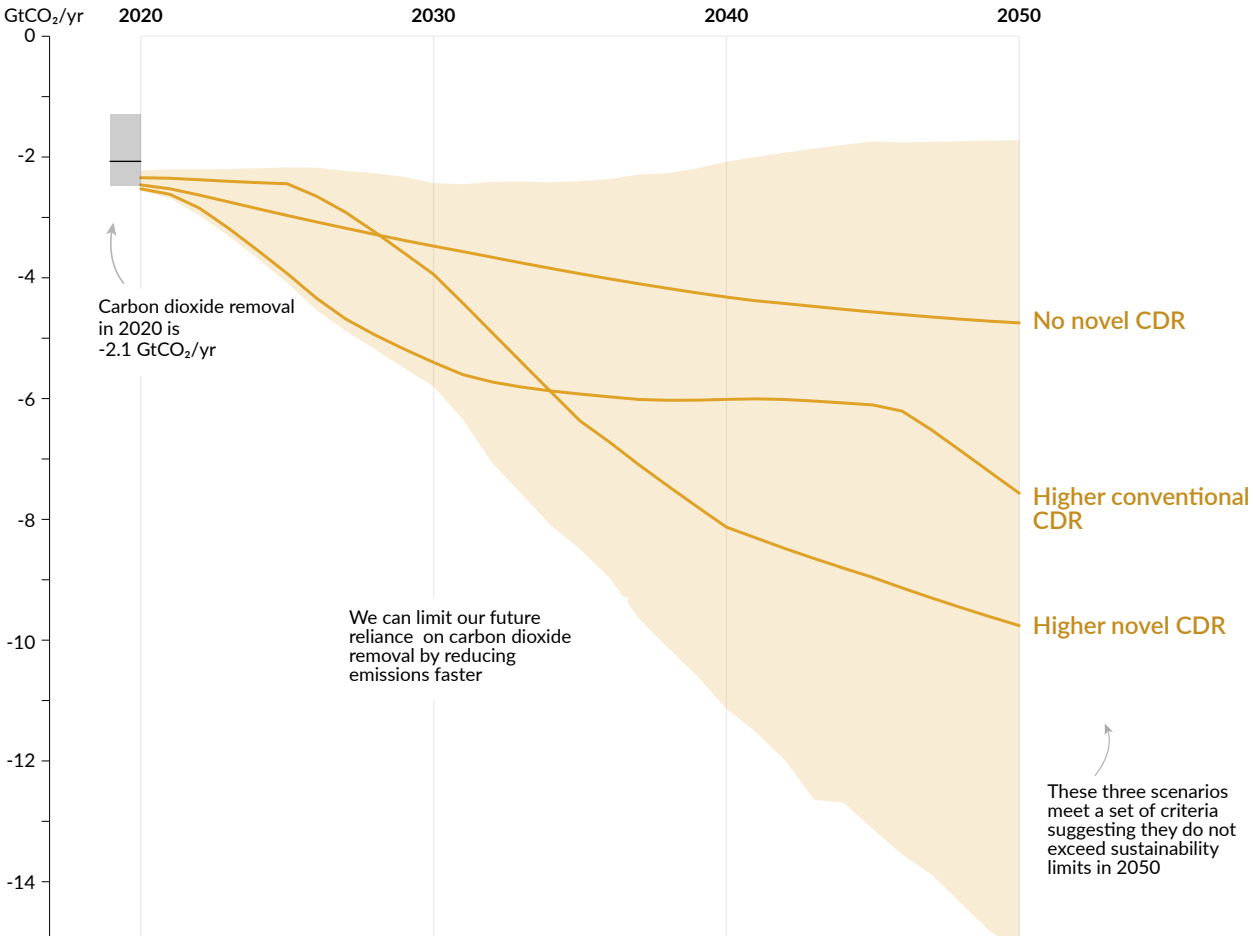
Greenhouse gas emissions continued to grow in 2023. This trend is incompatible with the Paris Agreement on climate change, regardless of how much CDR countries choose to deploy. The most important mitigation strategy in the near term is reducing emissions.

Alongside rapidly reducing emissions, *removing* carbon dioxide ($CO_2$) from the atmosphere is also necessary to meet climate goals. Precisely how much CDR will be needed, and where it will be deployed, depends on an array of factors, including the peak temperature reached as well as how quickly and by how much emissions are reduced.

Although the Paris Agreement states that climate change mitigation must be done "in the context of sustainable development", most scenarios do not explicitly consider social and environmental sustainability. We therefore identified a subset of scenarios that can be considered "more sustainable". Across this group of scenarios, the central range of CDR deployment is 7 to 9 $GtCO_2$ per year in 2050. The lowest scenarios reach 4 $GtCO_2$ per year in 2050. While this range is similar in 2050 to that for all below 2°C scenarios, the more sustainable scenarios cumulatively remove 170 $GtCO_2$ between 2020 and the time of net zero $CO_2$, compared with 260 $GtCO_2$ cumulatively in all below 2°C scenarios.

**Carbon dioxide removal is a feature of all 1.5°C scenarios that meet the Paris temperature goal, in addition to reducing emissions**

Carbon dioxide removal ($GtCO_2/yr$), in 2020 and in three Paris-consistent 1.5°C scenarios




## 2. Some CDR deployment is occurring, albeit at a low level.

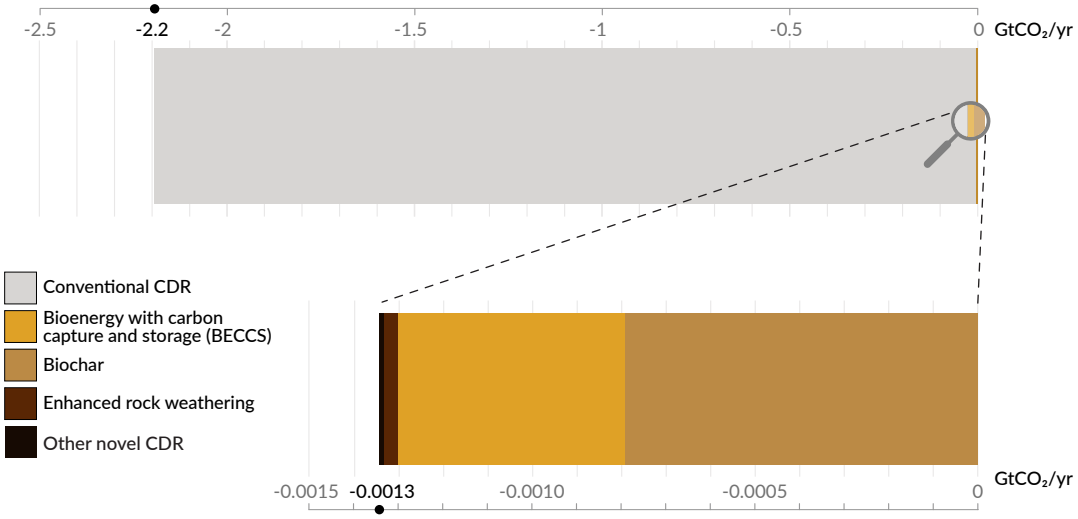
CDR is human activity that captures $CO_2$ from the atmosphere and stores it for decades to millennia. There are many CDR methods, which cover a variety of ways to capture and store $CO_2$. These methods have different levels of readiness, potential and durability. Each method has sustainability risks that could limit its long-term deployment. When deployed alongside measures to explicitly address sustainability risks, some methods can provide benefits beyond climate change mitigation.

Around 2 $GtCO_2$ per year of CDR is taking place already. Almost all of this comes from conventional CDR methods – those methods that are well established and widely reported by countries as part of land use, land-use change and forestry (LULUCF) activities – principally through afforestation/reforestation. These methods have delivered a relatively stable rate of CDR over the past two decades. Novel CDR methods – which are generally at an earlier stage of development than conventional CDR – contribute 1.3 million tons (0.0013 Gt) of $CO_2$ removal per year. That is less than 0.1% of total CDR, but novel

methods are growing more rapidly than conventional methods, despite a downward revision in our estimates compared with *The State of Carbon Dioxide Removal* 1st edition. Of this 1.3 million tons, less than 0.6 million tons per year involves geological storage of $CO_2$, which represents some of the most durable forms of CDR.

**Only a tiny fraction of all carbon dioxide removal results from novel methods**

Total amount of carbon dioxide removal, split into conventional and novel methods ($GtCO_2/yr$)




*Amount of carbon dioxide removal (CDR) is the sum of conventional CDR (2013-2022) and novel CDR (2023)*

## 3. To scale up CDR, innovative activity needs to intensify, of which we see robust evidence.

*Innovation* here is broadly construed: a sequence of interconnected activities, characterized by technology push and demand-pull factors, all influenced by policymaking and public perceptions. Innovation is key to scaling up CDR, as well as to improving its sustainability, for example through increasing removal efficiency.

Indicators of innovation show that activity is generally intensifying, although with some recent slowdowns:

- Research: Steady growth is seen in grant funding for CDR research projects (14% per year) and publications (19% per year). Both cover an increasingly diverse portfolio of CDR methods.
- Inventions: After a period of rapid growth, patents in CDR have declined since 2010. However, patents have become more diverse and novel methods play a larger role.
- Demonstrations: Some major demonstration programmes have launched recently, in the US (the Regional Direct Air Capture Hubs programme) and at the international level through Mission Innovation.

- Startups: Investment in CDR startups has grown significantly over the past decade, outpacing the climate-tech sector as a whole – although it declined in 2023, and CDR accounts for just 1.1% of investment in climate-tech start-ups.
- Company announcements: Companies show ambition to reach, by mid-century or sooner, levels of CDR consistent with meeting the Paris temperature goal, albeit with little grounds for credibility at present.
- Market activity: The voluntary carbon market is a nascent but growing source of demand for novel CDR. Conventional CDR from afforestation saw a drop in issuances and retirements in 2023, while purchase agreements grew sevenfold for future delivery of CDR via novel methods.

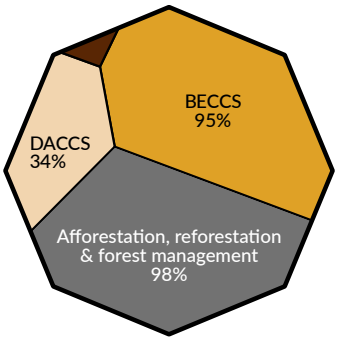
Because CDR methods carry different risks and benefits, and because it is uncertain how much CDR will be needed, deploying a diverse portfolio of methods is a more robust strategy than focusing on just one or two methods. Indicators of research, invention and investment in startup companies show evidence of diversification across CDR methods. However, current deployment and national proposals for future implementation are more concentrated on a few conventional methods. In addition, many modelled mitigation scenarios still represent only a limited set of CDR methods.

**Indicators of carbon dioxide removal (CDR) development show an emerging diversity of conventional and novel methods that is not yet seen in current deployment or national proposals**

## Research & innovation

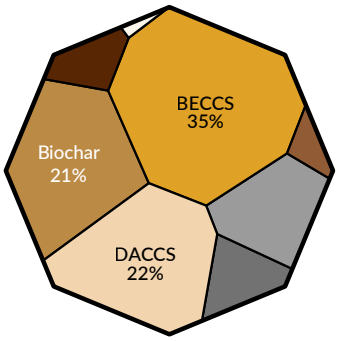
### Scenarios

% scenarios with CDR method (2023)
*total: 630 scenarios*




### Grant funding

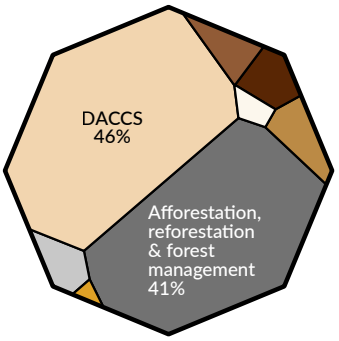
$ million per year (2018-2022)
*total: $685 million*




## Demonstration & upscaling

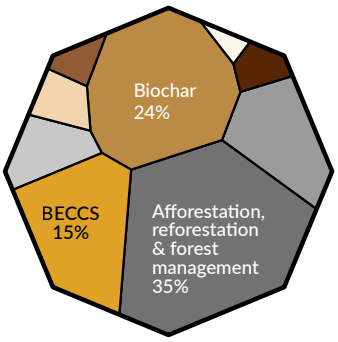
### Investments

$ billion per year (2018-2022)
*total: $2.8 billion*



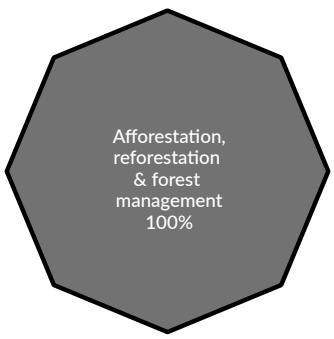

### High value patents

№ patents per year (2018-2021)
*total: 201 patents*




## Deployment of CDR

$GtCO_2$ (2023)
*total: -2.2 $GtCO_2$*




## National proposals of CDR

$GtCO_2$ (2030)
*total: -2.6 $GtCO_2$*


Each polygon is an indicator of carbon dioxide removal development and visualises the shares of ten CDR methods (conventional and novel). Higher fragmentation indicates greater diversity across methods.

**Conventional CDR methods**

- Afforestation/reforestation & forest management
- Peatland and coastal wetland restoration
- Soil carbon sequestration

**Novel CDR methods**

- Ocean fertilisation
- Direct air carbon capture and storage (DACCS)
- Bioenergy with carbon capture and storage (BECCS)
- Biochar
- Ocean alkalinity enhancement
- Enhanced rock weathering

Indicators of **research & innovation** and **demonstration & upscaling** show evidence of **diversity across CDR methods**, but many model scenarios still represent only a limited set of CDR methods.

The indicators of **deployment** and **national proposals** are more concentrated, showing almost **no diversity** across CDR methods.

*Deployment of carbon dioxide removal (CDR) is the sum of conventional CDR (2013-2022) and novel CDR (2023)*

## 4. To increase CDR innovation and scale-up, policies are needed that create demand for carbon removals.

Several jurisdictions are developing policies for CDR. These are often embedded in broader policy landscapes, for example as part of agricultural and industrial policy.

We see active efforts in technology push policy for CDR as evidenced by support for:

- Research projects
- Demonstration projects
- Emerging international coordination

But demand-pull policies, which would create demand for CDR, remain weak:

- Countries' nationally determined contributions and long-term strategies submitted to the UNFCCC contain few mentions of policies that would create considerable demand for CDR.
- Monitoring, reporting and verification (MRV), which is important for facilitating transactions in CDR markets, is not fully developed at present.

While CDR is starting to get more attention from policymakers in G20 countries, the voluntary carbon market is playing a key role in scaling up CDR. This is especially true for novel methods, although these still represent only a small fraction of total market-based CDR.

International collaboration on CDR is gaining momentum, for instance through Mission Innovation's CDR Launchpad, initiated in 2022. Proactively coordinating activities, policies and expectations has been important in developing analogous technologies, such as renewables.

## 5. Public awareness of CDR has been rising.

To develop and deploy CDR ethically and effectively, in many jurisdictions it is crucial to understand public perceptions.

Coverage of CDR in English-language social media and news media has grown rapidly, although news media coverage peaked in 2021 and declined in 2022 and attention on Twitter/X rose only slightly from 2021 to 2022. Coverage focuses on particular methods in particular countries, for example soil carbon sequestration in Australia and direct air capture in the US.

Key factors that influence public attitudes on CDR are perceptions of "naturalness" and ecosystem impacts, along with people's underlying values and beliefs – including about climate change.

Engaging actively with a variety of publics is both an opportunity and a challenge for CDR adoption and policy. Best practices are emerging that can enable practitioners to communicate responsibly about CDR.

## 6. Monitoring, reporting and verification (MRV) protocols are varied, proliferating and essential for scaling up CDR.

Robust MRV provides CDR activities with credibility and transparency, which are crucial to effective voluntary carbon markets, government-created markets, regulations and national reporting. However, at present the MRV ecosystem consists of many overlapping protocols, making comparison and oversight difficult.

MRV policymaking differs among jurisdictions. For example, the EU and the UK have prioritized developing CDR standards and guidelines; the US, meanwhile, has focused on scaling up market-ready CDR and developing MRV tools for specific applications, such as marine CDR. The voluntary carbon market has played a leading role, with projects developing methods for monitoring, reporting and verifying CDR projects.

We identified 102 MRV protocols for CDR. Sixty-three percent of these are for conventional CDR, 65% are for voluntary markets, and 58% are for international activity. Forty percent were developed since 2022.

The forthcoming IPCC methodology report (on CDR methods beyond LULUCF, carbon capture and storage, and carbon capture and utilization) is expected to outline a framework for including novel CDR methods in national inventories. This framework will likely guide best practice in the voluntary carbon market and the development of national policies.

## 7. There continues to be a gap between the amount of CDR in scenarios that meet the Paris temperature goal and the amount of CDR in national proposals.

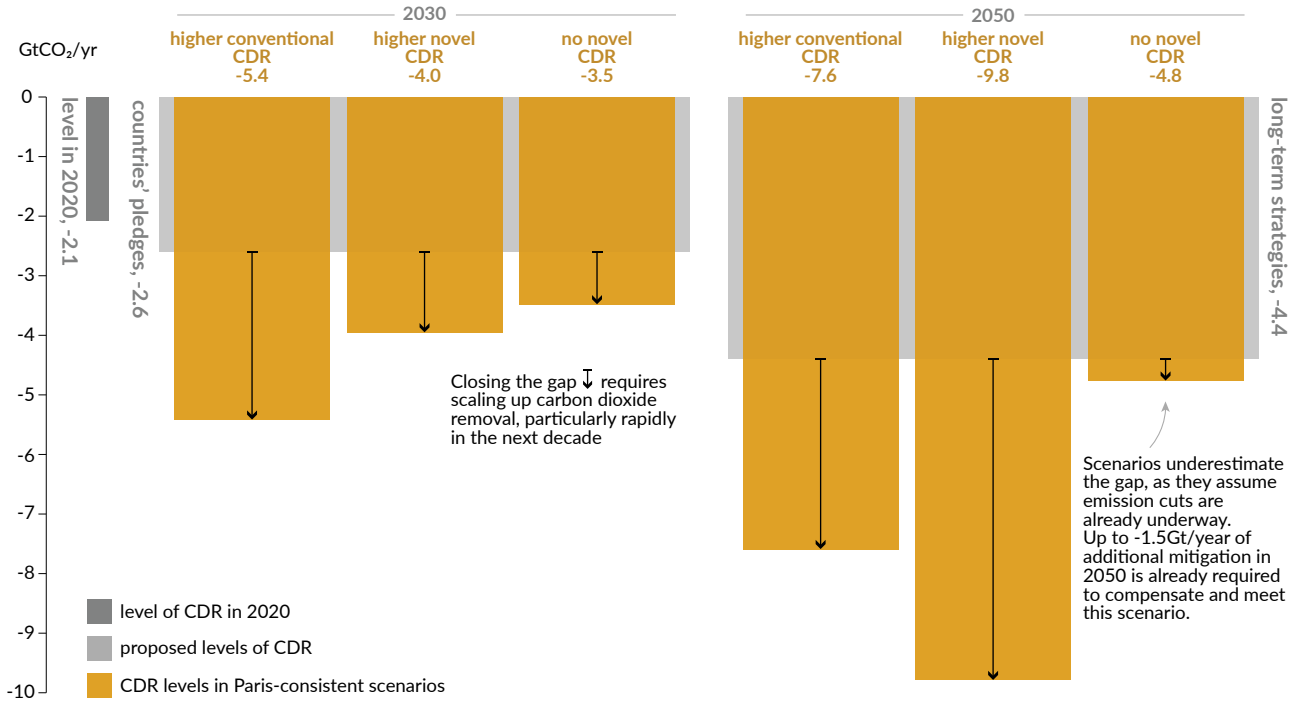
This report tracks the amount of CDR being proposed by governments, compared with the amount in scenarios that meet the Paris temperature goal. *Proposals* here includes the nationally determined contributions and long-term strategies that countries have submitted to the UNFCCC. The amount of CDR proposed falls short of what is required to meet the Paris temperature goal – this is the CDR gap. However, the CDR gap is small when the most ambitious national proposals are compared with levels in the *1.5°C with no novel CDR* scenario. The CDR gap for the three scenarios that more sustainably limit global temperature rise 0.9–2.8 $GtCO_2$ per year in 2030 and 0.4–5.4 $GtCO_2$ per year in 2050.

The actual gap is likely higher, because scenarios assume that significant emission reductions are already taking place, when in fact global emissions have continued to rise. Up to 1.5 $GtCO_2$ per year of additional mitigation through emission reductions and CDR is required by 2050 to compensate for these missed reductions in the case of the *1.5°C with no novel CDR* scenario. Meeting this additional mitigation requirement partly through CDR would imply a larger gap. There are limits, however, to CDR's capability to counteract inadequate efforts to reduce emissions.

The CDR gap can be closed by rapidly reducing emissions, scaling up a portfolio of both conventional and novel CDR methods, and explicitly integrating sustainability considerations into CDR policy. Continuing efforts to track the state of CDR – including gathering more precise and geographically disaggregated information on key indicators of CDR scale-up – can facilitate closing the CDR gap.

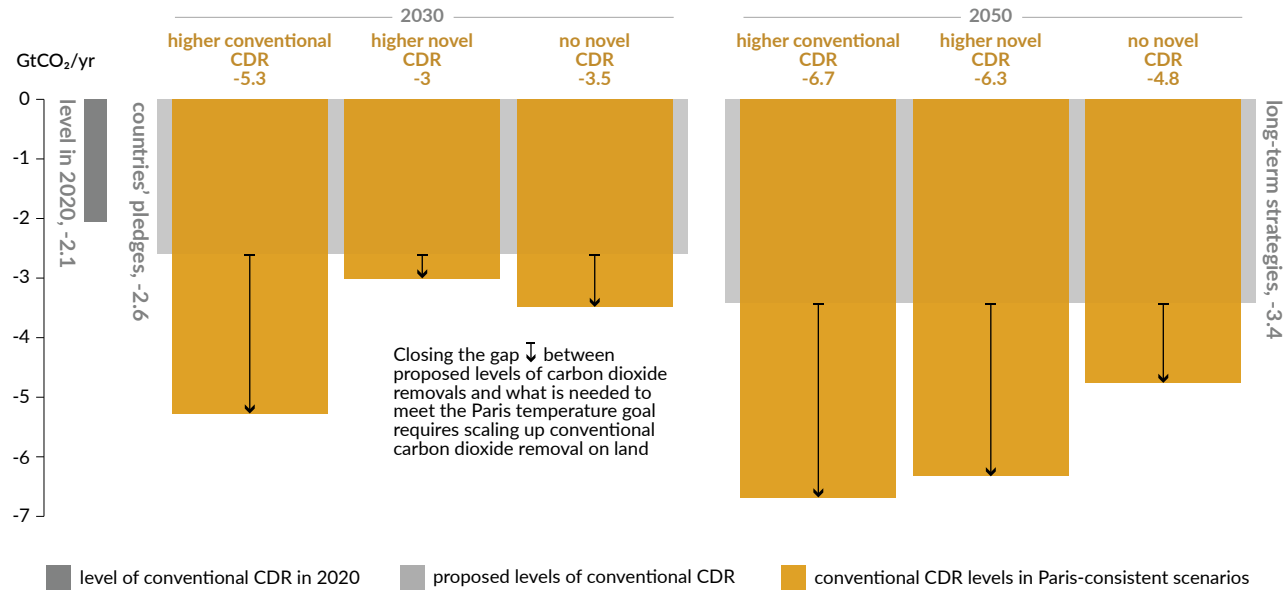
**There is a ↧ gap between proposed levels of carbon dioxide removal and what is needed to meet the Paris temperature goal**

Carbon dioxide removal ($GtCO_2/yr$), proposed levels compared to three Paris-consistent 1.5°C scenarios in 2030 and 2050

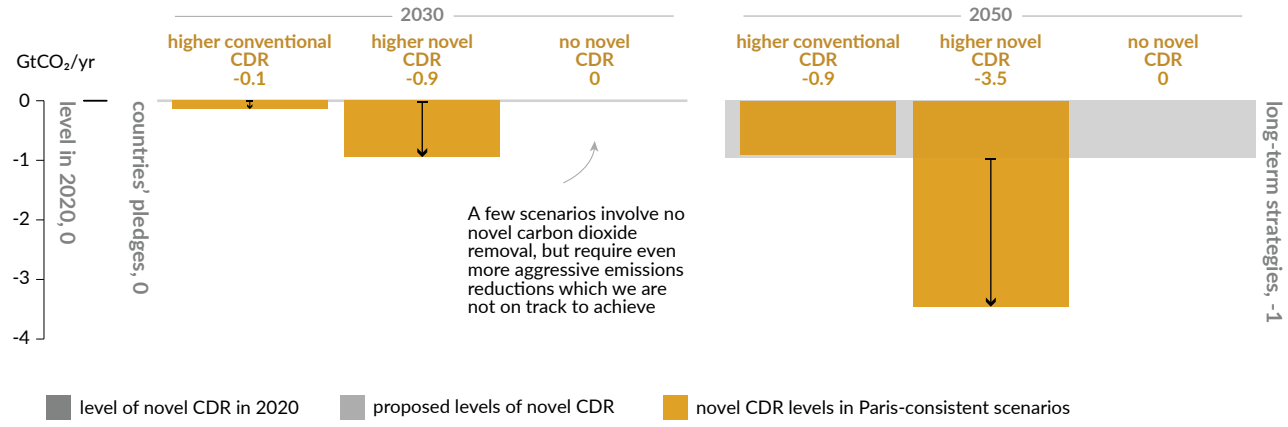


## There is a ↧ gap between proposed levels of conventional and novel carbon dioxide removal and what is needed to meet the Paris temperature goal

Conventional carbon dioxide removal ($GtCO_2/yr$), proposed levels compared to three Paris-consistent 1.5°C scenarios in 2030 and 2050




Novel carbon dioxide removal ($GtCO_2/yr$), proposed levels compared to three Paris-consistent 1.5°C scenarios in 2030 and 2050



executive summary

# THE STATE OF Carbon Dioxide Removal