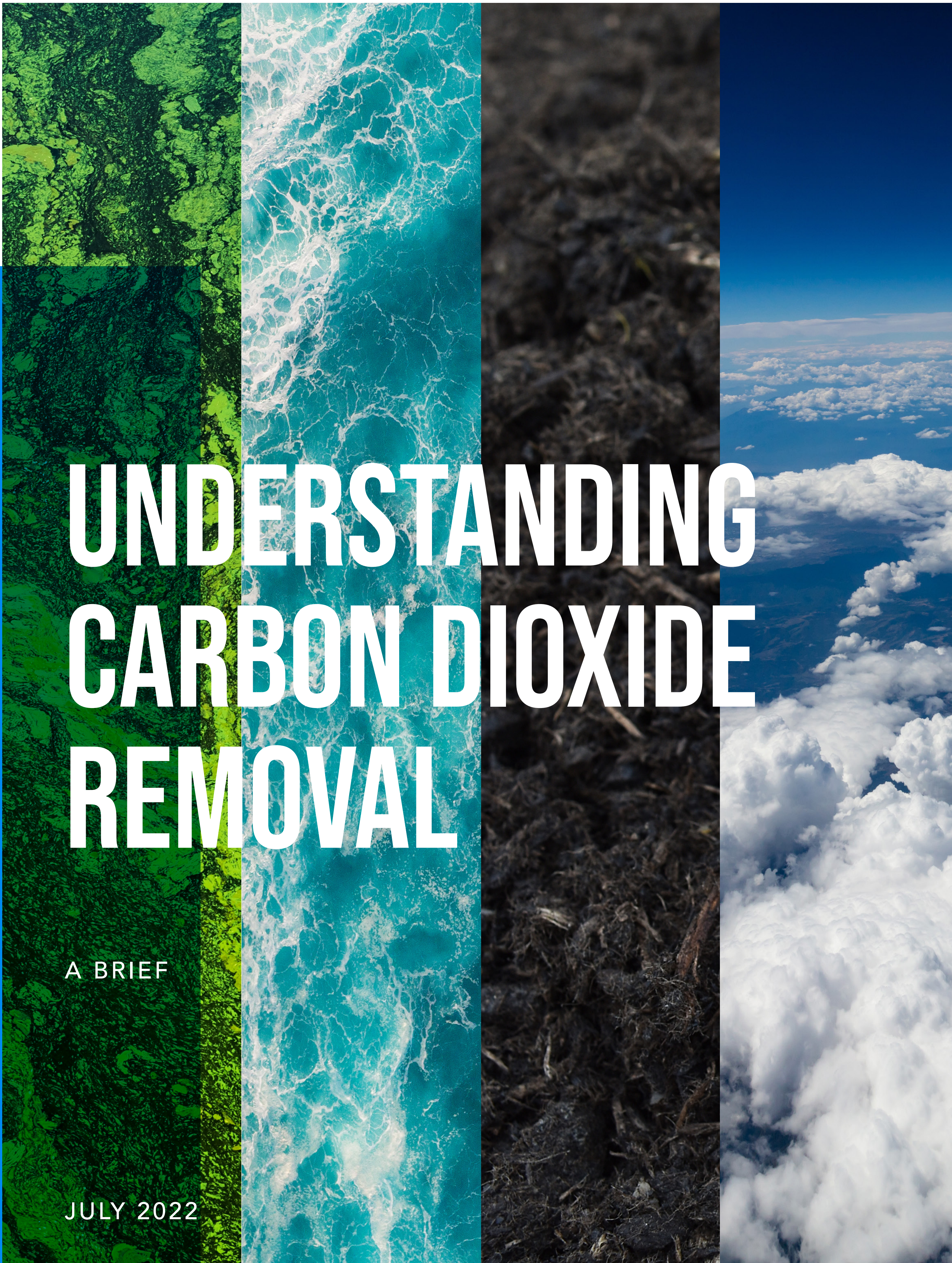


UNDERSTANDING CARBON DIOXIDE REMOVAL

A BRIEF

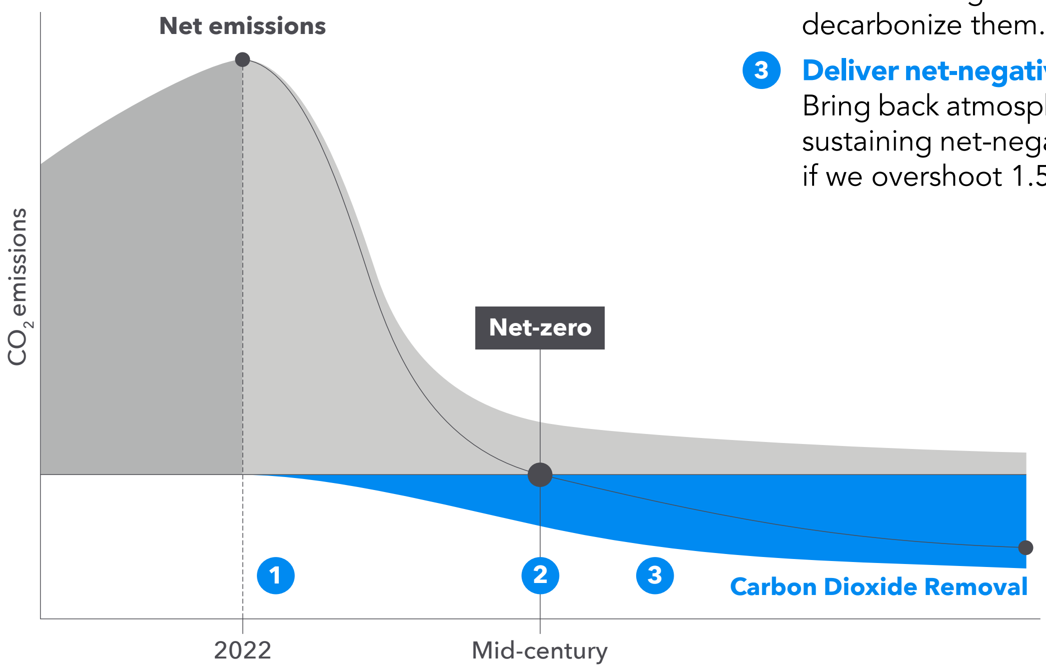
JULY 2022

Climate change is primarily caused by the accumulation of carbon dioxide (CO_2) in the atmosphere due to human activities. Stopping dangerous warming requires both aggressive emission cuts and the large-scale removal of carbon dioxide already in the atmosphere. Emission reduction is well understood, but what are the established and emerging techniques for carbon removal? How do these methods compare, and to what extent can they be a solution? What challenges remain to be overcome? This brief provides a base to begin exploring the possibilities of carbon removal.

What is Carbon Dioxide Removal (CDR)?

Carbon dioxide removal refers to "anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products."[1]. The climate impact of carbon removal is called 'negative emissions'.

Emissions Pathway: Large-Scale CDR



This illustration showcases how gross positive emissions differ from gross negative emissions, and how the sum of these two values (net emissions) could evolve from net positive today, to net zero by mid-century, to net negative thereafter. Please note that the carbon removal pathway presented here is only illustrative.

Why do we need carbon removal?

We must reach net zero CO_2 emissions by mid-century to have a chance of stabilising warming at or below 1.5°C and avoiding the worst impacts of climate change. Achieving net zero means a state in which all emissions are fully compensated for with an equal amount of carbon removal. Realistic pathways to meet this goal require deep emission cuts across all sectors coupled with rapid scale-up of removals, given the very limited remaining 1.5°C carbon budget. Virtually all climate mitigation pathways compatible with 1.5°C require substantial deployments of CDR as early as 2030, and at a scale of multiple billions of tonnes of CO_2 per year in the 2040s[1].

As a result, the importance of carbon removal in achieving net-zero has become established scientific consensus. The IPCC clearly states that "the deployment of CDR to counterbalance hard-to-abate residual emissions is unavoidable if net zero CO_2 or greenhouse gases (GHG) emissions are to be achieved"[1]. The report also identifies the three complementary roles that carbon removal must play in achieving our climate goals:

1. **Reduce net emissions before net zero (near-term)**
   Further reduce net CO_2 emissions on top of massive reduction efforts.
2. **Balance residual emissions (medium-term)**
   Balancing emissions that are very difficult to eliminate before the net zero date (putting the 'net' in net zero). Some emissions from specific sectors (steel, cement, chemicals, transport, agriculture) will need to be neutralized before the technologies and capabilities exist to fully decarbonize them.
3. **Deliver net-negative emissions (longer-term)**
   Bring back atmospheric CO_2 to safer levels by sustaining net-negative emissions, particularly if we overshoot 1.5°C of warming.

How does carbon removal work?

There are many ways to remove and store carbon (see summary on page 3), all of which require two distinct steps:

- **Extracting CO_2 from the air (or ocean*)**

  This can be achieved through various natural chemical processes underpinning the carbon cycle (such as photosynthesis, mineral weathering), as well as through engineered processes that selectively bind CO_2 molecules from the atmosphere.

- **Storing that carbon durably to keep it out of the atmosphere**

  Carbon can be stored in many reservoirs, including parts of the lithosphere (in specific rock formations), the biosphere (soils, vegetation), the hydrosphere (ocean and ocean sediments), or even the 'anthroposphere' (long-lived materials used by humans, especially building materials).

For some carbon removal methods, these two steps occur in the same location – for example, trees take in CO_2 and use it to build their roots, trunks, and leaves. In other cases, such as with direct air capture, extraction and storage occur separately, and the CO_2 may need to be transported from the extraction site to the geological reservoir where it is to be stored.

Is carbon removal the same as carbon capture?

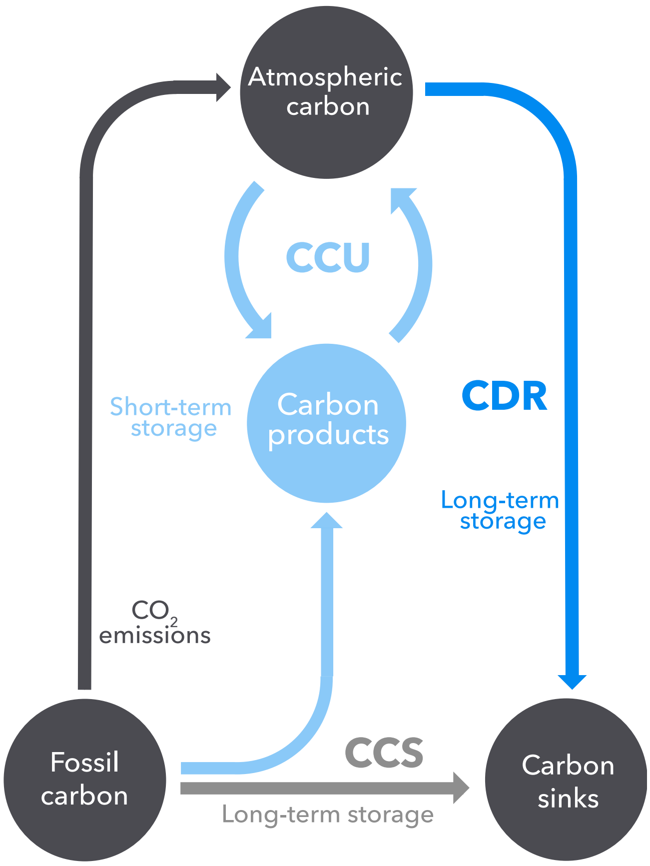
Carbon removal and carbon capture are part of a broader family of methods for 'carbon management', but they have different climate outcomes due to important differences in the source and destination of the CO_2[4].

Carbon capture and storage (CCS) is the capture of CO_2 from the exhaust stacks of industrial plants, followed by permanent storage in geological reservoirs. CCS is typically applied to plants that rely on fossil fuels and may enable some carbon-intensive industries to reduce emissions they cannot otherwise eliminate, but it does not support the drawdown of CO_2 from the atmosphere. CDR and CCS are distinct, but some CDR methods (e.g., direct air capture) may share the same long-term storage infrastructure used for CCS.

Carbon capture and utilisation (CCU), part of a broader set of 'carbon recycling' applications, is the reuse of captured carbon either directly (e.g., to fertilise greenhouses, in beverages) or as an ingredient in new products (e.g., concrete, fuels, chemicals). This utilisation can displace additional fossil fuel use, thereby eliminating emissions and reducing the carbon footprint of the product. In some cases, CO_2 is indeed taken from the atmosphere, but only resides in a product for a short time before being re-emitted to the atmosphere. This is utilisation, not removal, because there is no durable storage of the carbon.

Although CDR, CCS and CCU can all be valuable climate solutions, they provide different benefits and should not be confused.

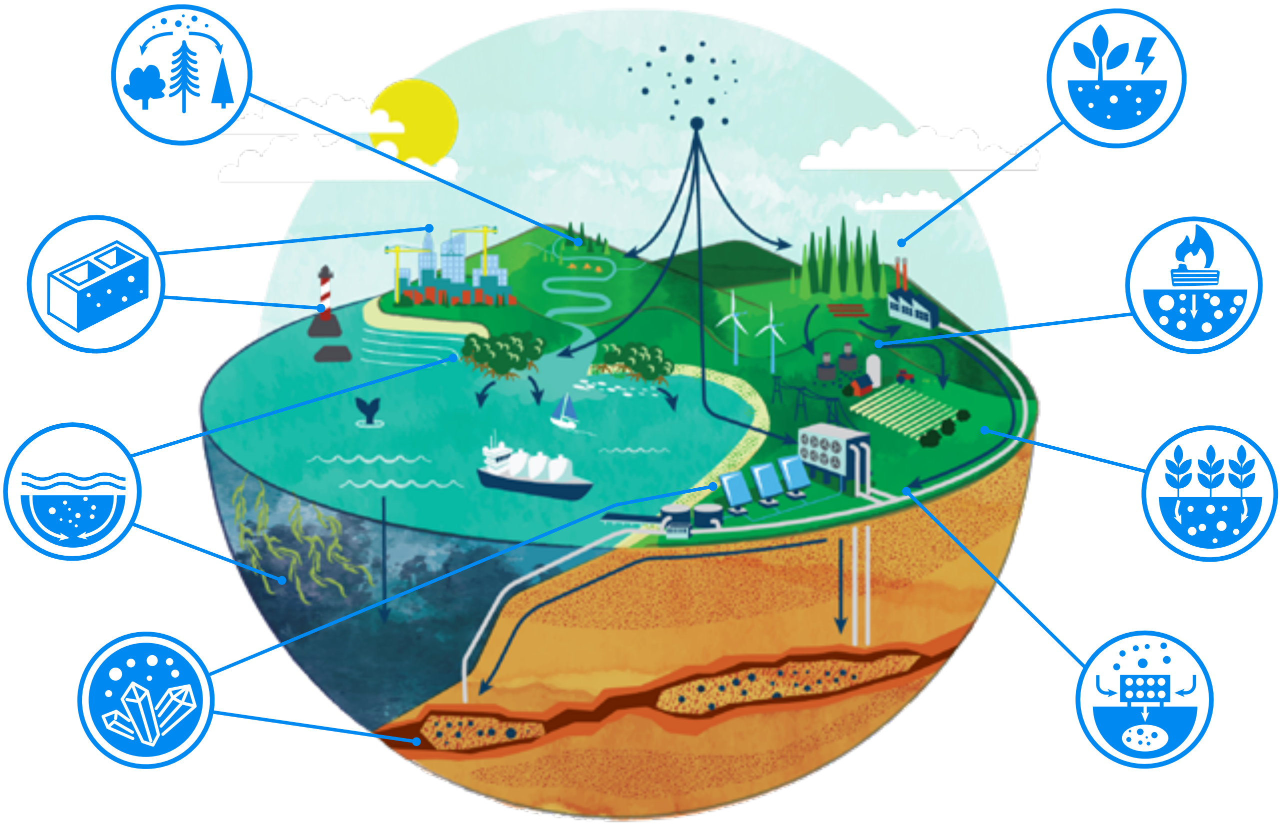
Carbon removal, capture, & utilisation



CDR is part of a family of 'carbon management' actions that also includes CCS and CCU.

* The removal of CO_2 from the surface ocean can be considered analogous to removing CO_2 directly from the air, since CO_2 readily exchanges between the air and the ocean. Ocean uptake of atmospheric CO_2 is the cause of ocean acidification, and reducing CO_2 concentrations in the atmosphere and/or ocean could potentially counter this effect.

Today's CDR methods[3]



Solutions for removing atmospheric CO_2 are fast-evolving and very diverse. This selection represents the most significant and well-known examples to date - many new solutions continue to be being proposed and developed.

Forestation
Planting and restoring forests and ensuring that the increased carbon level is maintained in perpetuity (trees store carbon in their trunk, branches, roots and in the surrounding soils).

Direct air carbon capture and storage (DACCS)
CO_2 is 'filtered' out of the ambient air (using a sorbent, solvent or other method), then stored in geologically-stable reservoirs.

Soils
Specific agricultural practices (e.g., no-till, improved soil management) lead to the absorption of carbon into soils, increasing the amount of stored carbon.

Ocean CDR
Several methods can stimulate marine bio or geochemistry to increase the ocean's capacity to pump carbon from the atmosphere and store it. Examples include ocean fertilisation, ocean alkalinity enhancement and blue carbon.

Biochar
By producing a stable, charcoal-like substance from biomass, absorbed carbon can remain locked in the biochar for decades to centuries. Biochar can be incorporated into products, or added to soils, where it may increase agricultural yields.

Mineralisation and enhanced weathering
CO_2 is incorporated and immobilized into rocks as a solid carbonate mineral, either by actively exposing crushed rocks that naturally react with CO_2 in the air or transporting a CO_2-rich fluid in underground rock formations.

Biomass carbon removal & storage (BiCRS)
Collecting streams of biogenic carbon (carbon that was previously removed from the air by plants and other lifeforms) and storing it durably. This could include carbon from non-energy applications like waste facilities and fermentation, or energy-producing applications, some of which are referred to as bioenergy with carbon capture and storage (BECCS).

Long-lived products
Certain building materials can store CO_2 over long periods, including timber (wood removes CO_2 as it grows) and concrete (e.g. aggregates from mineralised CO_2). Such removal methods must clearly address the stored carbon's fate at end-of-life. Very short-lived storage is of limited value, and considered "carbon recycling", not removal.

Illustration by Walker Cahall - www.waltronic.net

Profiling carbon removal options

Different carbon removal techniques have different characteristics, from physical parameters (total storage capacity, speed of removal, durability of storage) and economic considerations (cost, risk) to non-carbon co-benefits and social acceptability[5]. Each method has unique strengths and shortfalls – there is no 'one size fits all' solution and assessments of carbon removal potential show that we will need all available methods[6].

Removal potential

How much CO_2 can the method store? Each storage reservoir (e.g. a forest, an underground formation) has a maximum amount of CO_2 it can safely store before it fills up.

How quickly can the technique remove CO_2? It takes time to finance, permit, and deploy carbon removal projects - some methods, such as many forms of land-based carbon removal, can be more rapidly rolled out than others, such as constructing facilities for biomass carbon removal and storage. Once a carbon removal project starts operating, it has a maximum rate of removal it can deliver - newly planted forests, for instance, take decades to grow.

How long will the CO_2 be stored? Removed carbon is ideally locked away from the atmosphere in perpetuity. However, there is always a "risk of reversal" in which the stored carbon is released back into the atmosphere. Each carbon removal method has a different risk of reversal, making some methods more durable than others.

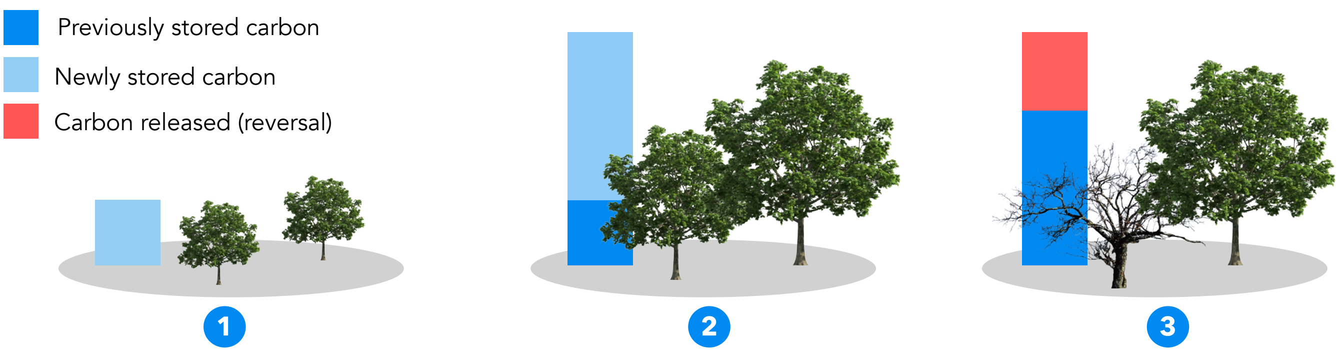
Other relevant parameters

Maturity - Some carbon removal methods,like sustainably-conducted reforestation, are mature. They can readily be deployed, and further optimisation to reduce costs is likely to be modest. Other methods like direct air capture or mineralization are well-understood but have yet to be widely deployed, and significant improvements and cost reductions are expected the more we deploy. Still other techniques, including some forms of ocean CDR, are very nascent and require further fundamental research to minimise risks and evaluate their real feasibility.

Costs - Today the cost of one tonne of CO_2 removed ranges from tens to thousands of euros. This reflects the differences in maturity of removal options, as well as their performance. In general, options that provide more durable storage are currently more expensive.

Resources - Each method has different requirements for inputs such as land, water, energy, or nutrients. Carbon removal must always be calculated on a net basis, accounting for any lifecycle emissions incurred in the removal process. However, even assuming precise lifecycle accounting, energy and material use could still have other knock-on effects or adverse outcomes that must be assessed and avoided.

Reforestation: Benefits & Risks[7]



Newly planted forests accumulate carbon over decades as they grow to maturity, eventually plateauing near their maximum CO_2 storage potential **(steps 1 to 2)**. Mature forests may continue to accumulate carbon but at a much slower rate. Above-ground carbon storage in the form of vegetation carries a constant risk of reversal that must be monitored, managed, and insured against. Natural disasters or dieback caused by wildfires, droughts, or disease, or the deliberate exploitation of forests for timber or development, all may lead to partial reversals of stored carbon back into the atmosphere, undoing the removal **(steps 2 to 3)** unless a specific party is held liable for remediating the reversal by removing and storing new carbon (for example, by conducting additional forestation). In general, the restoration of degraded forests (reforestation) with native species and avoiding infringing on land rights is acceptable practice, whereas other methods (e.g. afforestation, use of monocultures) are more debated.

Developing CDR at scale

Worldwide, we are not deploying carbon removal at anywhere near the scale required to reach climate goals: substantial upscaling is needed[8].

The growth of CDR is currently constrained by, notably:

- The lack of government policies and incentives to support CDR deployment and build the required visibility on carbon price on the long run.
- Low funding for R&D and innovation.
- A lack of certification frameworks to give buyers confidence in the quality of some carbon removal credits.
- Low public awareness and support.
- The availability of carbon storage capacity.

Each carbon removal method comes with novel challenges that need to be understood and confronted[2]. For example, direct air capture technologies currently require large amounts of energy, which must be generated by low-carbon sources. Land-based carbon removal, at large scale, can compete with other desired outcomes and land uses, such as biodiversity enhancement or food production, and can pose issues for land governance and ownership. Despite these constraints, some approaches can also provide various non-carbon co-benefits[9]: climate-resilient regenerative agricultural practices, the application of biochar to soils, or certain kinds of mineralization can deliver higher crop yields; reforestation can help to maintain ecosystem services and restore local biodiversity; many carbon removal methods improve livelihoods through new jobs and economic growth[1].

45 $GtCO_2$ per year

Current levels of emissions (as of 2019)[1]. This needs to be reduced as close to zero as quickly as possible. Anything we do not reduce must be removed.

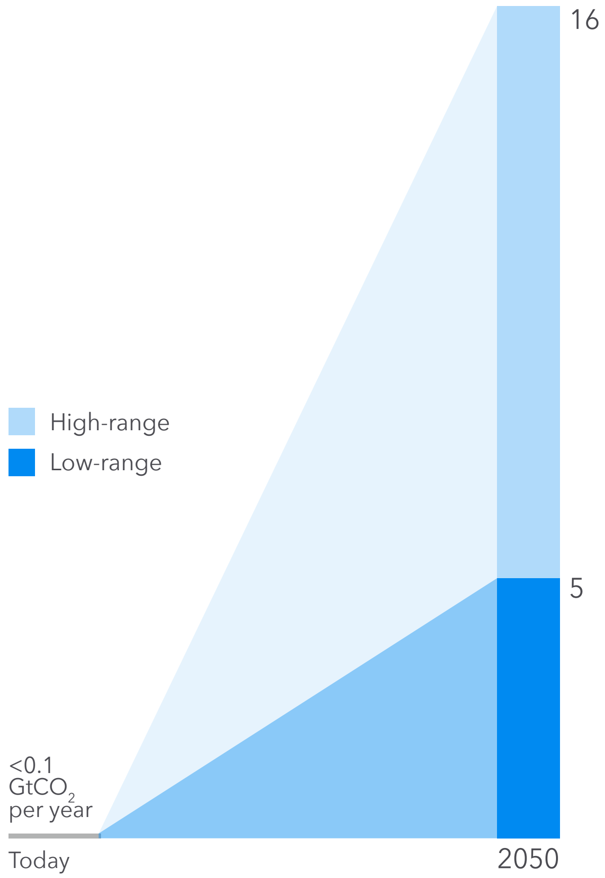
Some carbon removal methods urgently need early-stage support to research, development, and pilots. Other carbon removal methods are poised to begin ramping up deployment, but we are at the very beginning of a multi-decade journey to reach the scale required. Some carbon removal methods will need to follow the same path as renewable energy technologies, where early investments and deployment incentives from governments led to plummeting costs beyond what any had predicted[1].

Building a carbon removal industry will take time, and delaying action today will only constrain our ability to deliver removal at the scale required in the future.

Up to 5-16 $GtCO_2$ per year

may need to be removed by 2050 to stay within 1.5°C-compliant scenarios.[1]

Scaling CDR to 2050



Predicting required volumes of carbon removal is uncertain - the more emissions we eliminate the sooner, the less removal is required. Nevertheless, indicative ranges for the removal rate and total cumulative removals required to stay 1.5°C-compliant have been collated by the IPCC.

There is no silver bullet; we need a portfolio approach

No single carbon removal method can provide the volume of negative emissions required by 2030 or by 2050[6]. Moreover, each carbon removal method has its own strengths and weaknesses. For these reasons, a portfolio approach is necessary. Deciding which carbon removal methods to prioritise when and where is a matter of timing and local conditions. Carbon removal methods that are available today, such as forestation and other ecosystem restoration techniques, are typically lower-cost and come with significant non-carbon co-benefits. Provided their durability, additionality, effective measurement, and avoidance of adverse impacts can be ensured, they must be scaled up immediately[9].

However, the total potential and speed of these solutions is limited, notably by changes brought about by climate change itself[10].They must therefore be complemented with more nascent methods that may come at a higher cost, but that perform better on some dimensions such as maximum removal capacity or storage durability[11]. Such earlier-stage carbon removal methods need significant investment today to unlock their potential.

How should we think about carbon removal?

Carbon removal must never become a substitute for stringent and unprecedented emissions reductions. Allowing such substitution could create a moral hazard, reducing motivation to make those necessary cuts[12]. We can avoid this outcome by emphasising the importance of both emissions reductions and removals and separating them: pathways that keep warming within acceptable limits require halving emissions by 2030 and reducing far more by 2050, but they also require the removal of billions of tons of CO_2 from the atmosphere. Neither emission reduction nor removal is sufficient without the other.

Carbon removal can also play a role in delivering climate justice under a rigorous governance framework[13]. Developed countries, by virtue of their higher per capita emissions, wealth, and much larger historical contribution to climate change, will need to reach net zero sooner than developing countries, who will require more time for a smoother transition. Furthermore, carbon removal could provide a mechanism for countries to take responsibility for their historical emissions[14]. While some climate impacts are irreversible, using net negative emissions to begin addressing past emissions will act to reduce warming and eliminate some of the negative impacts caused by carbon build-up from centuries of unrelenting emissions.

The science is clear: carbon removal has a crucial role to play to get to net zero, but the sector and its regulation are not advancing at the speed that is required. Upscaling carbon removal must be done thoughtfully but ambitiously, considering the full array of available and potential methods and thoroughly assessing their climate impact, their non-carbon co-benefits, and any potential environmental or social impacts (novel risks). Addressing these challenges requires immediate policy action to support research, investment, deployment, and public engagement for carbon removal to play its part in the fight against climate change.

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Further readings

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