Climate change mitigation scenarios with a broad CDR portfolio

RESCUE

Science Summary

In February 2025, the European Scientific Advisory Board on Climate Change (ESABCC) published a report outlining recommendations for scaling up carbon dioxide removals (CDR) while addressing opportunities and risks. It highlights the urgent need for strong EU policies to expand CDR and counterbalance residual emissions from activities with no or limited mitigation alternatives. The report also underscores CDR's potential to drive innovation, restore ecosystems, and create economic opportunities while ensuring environmental and social safeguards.

However, before starting large-scale CDR deployment, we need to understand its potential impacts on Earth's systems and assess its feasibility and speed in bringing temperatures back down. To support this, the RESCUE project has developed a set of scenarios to understand the role of CDR in reaching different temperature limits and exploring pathways for reversibility after a temporal overshoot.

Temperature overshoot

A temperature overshoot is the period when global temperature rises above 1.5°C before falling back to that level. Temperatures can start to decrease if, after reaching net-zero CO_2 emissions, carbon sinks remove more CO_2 than is still being emitted, such that the net emissions turn negative.

Since the exact temperature rise per unit of CO_2 emitted is uncertain, there is some unpredictability in temperature during an overshoot. Additionally, the impacts of a temporary overshoot are also unclear. Depending on the magnitude and duration, a temperature overshoot may increase risks such as triggering tipping points in Earth's systems, biodiversity loss, sea level rise, and other long-term, irreversible changes. As a result, even if temperatures return to 1.5°C, the impacts of the overshoot itself may not be reversible.

Scenario variables

Temperature target

The temperature target is defined by the carbon budget. The carbon budget is the cumulative amount of CO_2 emissions (expressed in gigatons, Gt) allowed over a specific period to stay within a given temperature threshold. Thus, exceeding the carbon budget can lead to a temperature overshoot. RESCUE scenarios consider two targets:

1.5°C: A carbon budget of **500 Gt CO_2** starting from the beginning of 2020, implies a 50% likelihood of limiting global warming to 1.5°C.

2°C: A carbon budget of **1150 Gt CO_2** starting from the beginning of 2020, implies a 67% likelihood of limiting global warming to 2°C.

Climate policy stringency

Two different levels of climate policy stringency, indicate the scenario's flexibility for a temperature overshoot and allowance to exceed the respective carbon budget:

Low overshoot (Low OS): No carbon budget exceedance is allowed at any point in the 21st century, ensuring minimal or no temperature overshoot. These scenarios assume immediate climate policy action.

High overshoot (High OS): Temporary exceedance of the carbon budget is allowed. However, in these scenarios, cumulative CO_2 emissions need to return to the carbon budget target by the end of the century via large-scale CDR. These scenarios represent a world with delayed climate policy.

CDR portfolio

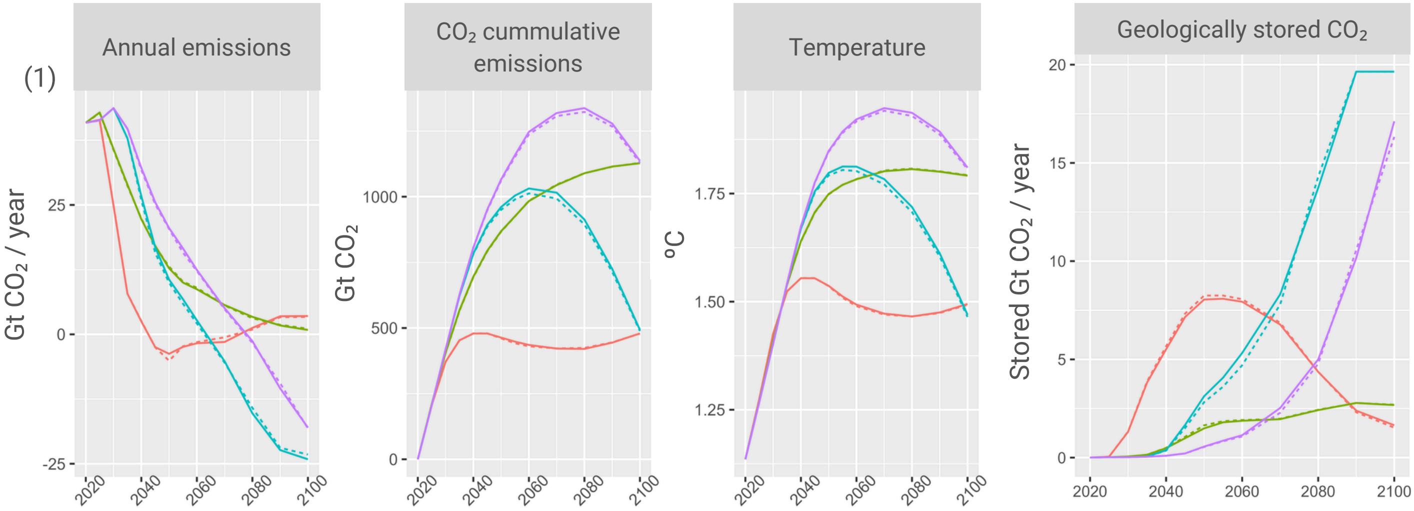
Scenarios differentiate if their CDR portfolio counts with the method Ocean Alkalinity Enhancement (OAE), in other to taste the sensitivity of having it available. All scenarios include Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Carbon Capture and Storage (DACCS), Industry CDR and Afforestation.

OAE on: Scenarios include OAE.

OAE off: Scenario do not include OAE.

Scenario results

Scenarios	1.5°C, low OS	1.5°C, high OS	2°C, low OS	2°C, high OS	OAE off (solid line) / OAE on (dotted line)
Temperature in 2100	1.49 °C	1.47 °C	1.79 °C	1.81 °C	
Peak warming	1.56 °C	1.81 °C	1.80 °C	1.94 °C	
Year of reaching the carbon budget target	2043	2100	2100	2100	
Year of net-zero CO_2 emissions	2043	2063	after 2100	2078	



In the two high OS scenarios, the timing of net-zero CO_2 differs by only 15 years. This suggests that **delaying the transition significantly reduces the flexibility for climate policy adjustments needed to shift from a 2°C to a 1.5°C compatible pathway.**

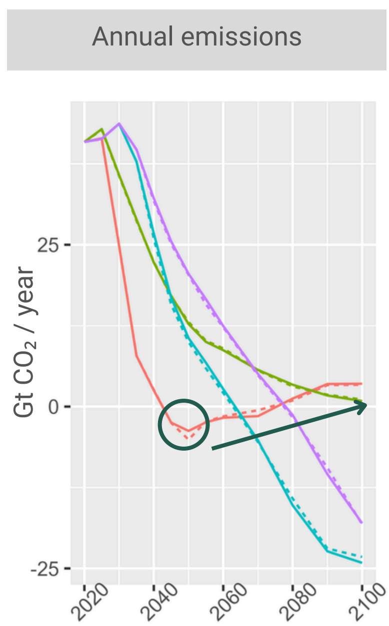
Not all carbon captured is stored geologically (CCS), some is used in the the energy sector through Carbon Capture and Utilization (CCU). In the 1.5°C scenarios, a higher percentage of captured CO_2 is stored. This means that **stricter temperature targets leave less CO_2 available for uses such as synthetic fuel production.**

Behind the low OS scenarios: Why emissions increase after net zero

The low OS and high OS emissions scenarios provide direct policy advice by offering consistent future pathways that demonstrate how these scenarios differ in terms of mitigation challenges. Specifically, they highlight how the scale-up speed of CDR differs between the scenarios.

However, the policy role of these scenarios contrasts with the basis of the experimental design. These scenarios are carefully designed to ensure that meaningful conclusions can be drawn from Earth System Model (ESM) experiments. In particular, when follow-up temperature reversibility experiments are performed, it is crucial that both low OS and high OS scenarios reach the same cumulative CO2 emissions by 2100. Due to inertia in the economic system, the fast ramp-up of CDR leads to some net-negative emissions after the peak, reducing cumulative emissions below the target value. To still reach 500 Gt CO2 by 2100, emissions briefly rise again in the second half of the century. This creates a tension between the scenarios' suitability for policy advice—whether a scenario with rising emissions can be labeled as Paris compatible—and experimental design, which requires exactly 500 Gt CO2 in 2100.

This tension between policy advice and experimental design explains why emissions in the low OS 1.5° scenario rise again after reaching net-zero. This is a necessary adjustment to meet the cumulative emissions target by 2100.



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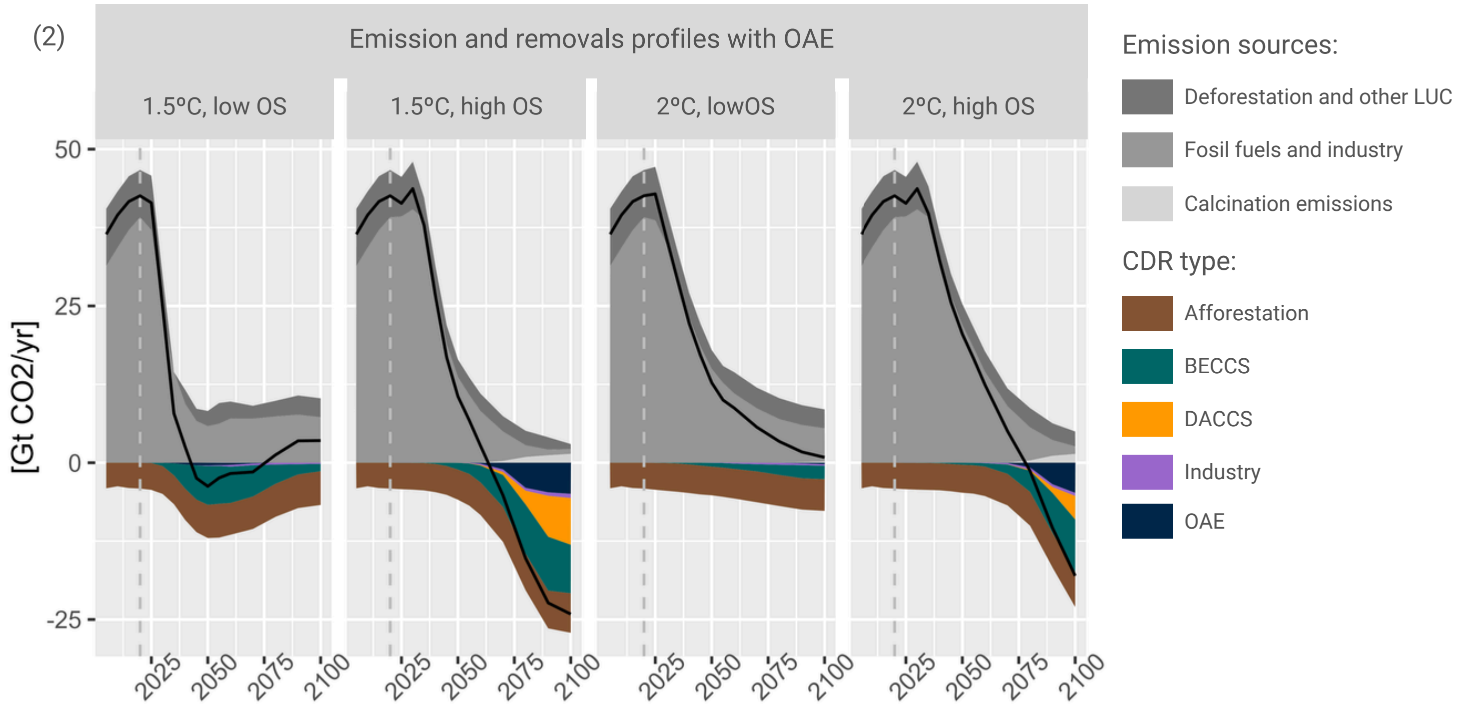

Near-term investments in CDR are crucial in addition to strengthened early mitigation. Only early mitigation in combination with a relaxed temperature target (2°C, low OS) would allow for slower CDR expansion rates. Therefore, near-term investments in CDR are important, as a large-scale and fast deployment may become inevitable regardless. The 1.5°C scenarios show that large-scale CDR and high expansion rates are inevitable to keep temperatures below this threshold. In the 1.5°C, low OS scenario, the strict carbon budget requires an early and rapid scale-up of CDR. However, in high overshoot scenarios, despite delayed action, the maximum CDR growth rates remain similar. This means that **delaying emissions reductions doesn't slow the CDR scale-up but simply shifts the period of intense growth to a later time**. Additionally, a high overshoot demands a substantially greater overall deployment of CDR.

If OAE is available, it often substitutes Direct Air Carbon Capture and Storage (DACCS), while other CDR and CCS technologies remain largely unaffected. OAE and DACCS have similar properties: both potentially provide carbon to the economy (OAE via limestone calcination) and have similar energy requirements. In regions with techno-economic properties slightly better for OAE, this technology prevails.

For further reading on the policy implications of these scenarios, **read our policy brief**:

References

Strefler et. al (2021), Carbon dioxide removal technologies are not born equal. DOI: 10.1088/1748-9326/ac0a11

Bauer et. al (2023), Exploring risks and benefits of overshooting a 1.5 °C carbon budget over space and time. DOI: 10.1088/1748-9326/accd83

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