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Final report

Targeting Climate Politics

Geoengineering, Governance, and Global Goals

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Abstract: Targeting Climate Politics – Geoengineering, Governance, and Global Goals.

Climate change is an increasingly urgent problem. Although the Paris Agreement signalled a commitment to a climate target of 2°C, or even 1.5°C, current national commitments and emissions trends do not track with these targets. Against this backdrop, alternative technological approaches to climate change have emerged as a possible approach. By limiting the damages of climate change through large-scale environmental interventions, such 'geoengineering' technologies could, potentially, limit the damages of climate change. The removal of carbon dioxide from the open atmosphere, called carbon dioxide removal (CDR), might serve to lower carbon concentrations, lessening the greenhouse effect and corresponding climate effects. Furthermore, enhancing the reflectivity of the Earth through solar radiation modification (SRM) may artificially lower global temperatures. However, many scientists, civil society organisations, and politicians do not see geoengineering technologies, especially SRM, as a desirable approach. Such technologies might lead to mitigation delays, political conflict, and uncertain climatic effects. This report outlines major questions around geoengineering technologies – both CDR and SRM – investigating its technical and environmental components as well as anchoring it in the context of of a target-driven climate and sustainability politics. Based on these components, the report provides several recommendations for policy.

Kurzbeschreibung: Klimapolitik im Visier – Geoengineering, Governance und Globale Ziele.

Der Klimawandel ist ein zunehmend dringendes Problem. Das Pariser Abkommen hatte das Ziel, die Erderwärmung auf 2 °C, oder sogar 1,5 °C, zu begrenzen, doch die aktuellen nationalen Verpflichtungen und Emissionstrends entsprechen nicht diesen Zielen. Vor diesem Hintergrund sind alternative technologische Ansätze zum Klimawandel als mögliche Lösung aufgetaucht. Durch großflächige Umweltinterventionen könnten sogenannte „Geoengineering"-Technologien potenziell die Schäden des Klimawandels begrenzen. Die Entfernung von Kohlendioxid aus der Atmosphäre, auch bekannt als Kohlendioxid-Entfernung (CDR), könnte dazu beitragen, die Kohlenstoffkonzentrationen zu senken, was den Treibhauseffekt und die entsprechenden Klimafolgen verringern würde. Zudem könnte die Erhöhung der Reflektivität der Erde durch Solarstrahlungsmodifikation (SRM) die globalen Temperaturen künstlich senken. Viele Wissenschaftler*innen, zivilgesellschaftliche Organisationen und Politiker*innen sehen jedoch Geoengineering-Technologien, insbesondere SRM, nicht als wünschenswerte Lösung an. Solche Technologien könnten zu Verzögerungen bei der Minderung, politischen Konflikten und ungewissen klimatischen Auswirkungen führen. Dieser Bericht umreißt zentrale Fragen zu Geoengineering-Technologien – sowohl CDR als auch SRM – und untersucht deren technische und ökologische Komponenten, während er sie im Kontext von zielorientierter Klima- und Nachhaltigkeitspolitik verankert. Basierend auf diesen Komponenten bietet der Bericht mehrere politische Empfehlungen an.

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List of Abbreviations

Acronym	Explanation
AFOLU	Agriculture, Forestry and Other Land Use
AMOC	Atlantic meridional overturning circulation
BECCS	Bioenergy with Carbon Capture and Storage
BMBF	Bundesministerium für Bildung und Forschung (Federal Ministry of Education and Research)
CBD	Convention on Biological Diversity
CCT	Cirrus cloud thinning
CDR	Carbon dioxide removal
CCS	Carbon Capture and Storage
CCUS	Carbon Capture and Utilization/Storage
CERF	Civil Engineering Research Foundation
Climate Engineering	Geoengineering (for the purposes of this report)
CO2	Carbon dioxide
DAC	Direct air capture
DACCS	Direct Air Carbon Capture and Storage
GGR	Greenhouse Gas Removal (s. CDR)
GHG	Greenhouse Gas
Gt	Gigaton
IAM	Integrated Assessment Modelling
IPCC	Intergovernmental Panel on Climate Change
MCB	Marine cloud brightening
mCDR	Marine carbon dioxide removal
NAS	U.S. National Academy of Sciences, Engineering, and Medicine
NET	Negative Emissions Technologies
oCDR	Oceanic carbon dioxide removal (see mCDR)
OAE	Ocean Alkalinity Enhancement
RRI	Responsible Research and Innovation
SAI	Stratospheric aerosol injection
SDGs	Sustainable Development Goals

Acronym	Explanation
SRM	Solar radiation modification, solar radiation management, solar geoengineering
tCDR	Terrestrial carbon dioxide removal
UBA	Umweltbundesamt (German Environment Agency)
UNFCCC	United Nations Framework Convention on Climate Change
UV	Ultraviolet

Summary

Climate change is an increasingly urgent problem. Although the international community of nations has committed to a climate target of 2°C, or even 1.5°C in the Paris Agreement current national commitments and emissions trends do not track with these targets. Most projections place end-of-century warming somewhere between 2°C and 3°C. Moreover, concerns over the possible crossing of various tipping points in the climate system also intensify, with scientists fearing the collapse of the Atlantic merodional overturning circulation (AMOC) (Van Westen et al., 2024), irreversible thawing and melting of the Greenland and Antarctic ice sheets (Armstrong McKay et al., 2022), and the collapse of the Amazon rainforest (Lovejoy & Nobre, 2018). Yet at the same time, the question of climate change is beset by evermore intractable concerns. Can the climate targets of the Paris Agreement even be met? In which ways can a warming 1.5°C or even 2°C still be achieved given the demands of current socioeconomic and political systems? How drastic will the necessary rapid changes in lifestyle, mobility and economic production be? On the other hand, what is the leverage effect of technological breakthroughs in energy generation, energy storage and climate technologies in counteracting environmental degradation?

Against the backdrop of these highly charged political issues, a series of scientific and technological proposals, which have historically been referred to as ‘geoengineering’, and are now being considered as a possible approach to climate change. Although the term has a much broader and more complicated history, geoengineering in recent years has become synonymous with the Royal Society’s 2009 definition, “deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change”. Such approaches envision the deliberate manipulation of planetary geological, atmospheric, and bioecological systems to counter-cool the planet. In that sense, geoengineering technologies ostensibly appear as an approach to safeguard the future of humanity and biodiversity on Earth by potentially limiting the damages wrought by climate change through large-scale environmental interventions. The removal of carbon dioxide from the open atmosphere, called carbon dioxide removal (CDR), might serve to lower carbon concentrations, lessening the greenhouse effect and corresponding climate effects. If such a way to address the root cause of climate warming does not suffice, climate interventions may also artificially lower global temperatures, by enhancing the reflectivity (also known as albedo) of the Earth, in an approach called solar radiation modification (SRM). However, many scientists, civil society organisations and politicians do not see geoengineering as a possible solution or a desirable approach. Rather, they fear that geoengineering technologies might only risk to exacerbate the problem, leading to mitigation delays, greenwashing, political conflict, or even the intensification of extractive practices. Moreover, while it is tempting to address geoengineering as an approach specifically tailored to concerns about climate change, in reality these technological approaches intersect with many many geophysical, atmospheric, and bioecological processes, as well as with political and social concerns.

The question of geoengineering appears within the larger context of climate and sustainability politics, shaped, amongst others, by the framework of the United Nations Sustainable Development Goals (SDGs). The SDGs, established in 2015, aim to achieve global sustainable development by 2030 with participation from all United Nations member states. These goals cover a wide range of socio-economic objectives while emphasizing climate action and biodiversity conservation. Geoengineering proposals both intersect with such political targets and aims and are influenced by similar political forces.

This report outlines major questions around geoengineering technologies – both CDR and SRM – investigating its technical and environmental components as well as anchoring it in the context of a target-driven climate and sustainability politics. Based on these components, the report provides several recommendations for policy. Key recommendations and findings include:

- **Neither SRM nor CDR can be an alternative to rapid decarbonisation**. The idea that CDR can be used to offset remaining emissions - with the sole exception of narrowly defined emissions that are difficult to avoid - is problematic. Statements suggesting that SRM could - for whatever reason - be used as a reason to slow down climate protection should be actively refuted.
- **Governance risks** are a key concern for all geoengineering technologies. Beyond questions of mitigation deterrence, questions of responsibility (diffuse or centrally organised, directive or market-based), such questions include **future-proofing** governance procedures, addressing questions around the future stability and governance of both carbon capture and carbon sinks, as well as SRM procedures.
- Existing model projections may be **overly optimistic** about both SRM and CDR, as many projections assume that orderly, agreed upon, and economically optimal implementation. In political reality, such an optimised implementation seems unlikely.
- The **potential** for CDR remains highly uncertain, with estimates of their costs and scale varying greatly.
- **Ecological consequences, social feasibility, acceptance, and justice** of CDR methods will need to be incorporated in assessment procedures and in policy projections as soon as possible. Such considerations will inevitably affect the scope and scale of CDR potential.
- While the **SDGs** serve well as a reflection of global politically agreed-upon priorities, **assessing CDR or SRM directly against these goals** is **unlikely to provide** a sufficiently **comprehensive understanding** of the technologies' political desirability or environmental impacts.
- Importantly, **current political and scientific practices**, including political deadlines and targets, may have the unintended consequence of pushing geoengineering technologies – both CDR and SRM – into view, **without adequate democratic or political deliberation**.
- **Decision-making around SRM** will be difficult to do democratically, as it requires global decision-making capacity, informed consent over deeply complex issues, and private and national interests. There is a potential tension between the **just implementation and national (or even commercial) interests.**
- SRM technologies aimed to counteract warming on a global scale are **highly risky and uncertain**. Serious negative effects and costs would have to be accepted. Moreover, SRM does not address detrimental effects of climate change beyond those directly related to warming, such as ocean acidification.
- SRM may lead to power struggles and **geopolitical conflict**. The uneven distribution of impacts, e.g., on precipitation patterns or the risk of extreme weather events between regions and countries holds the potential for geopolitical tensions.

- **An agreement restricting the *use* of SRM and governing research practices is urgently necessary**. The exact form of such a non-use agreement should be subject to political debate, led at least in part by expertise in the social sciences.

Zusammenfassung

Der Klimawandel stellt ein immer dringlicheres Problem dar. Obwohl die Staatengemeinschaft im Pariser Abkommen festgelegt hat, den globalen Temperaturanstieg auf deutlich unter 2°C und möglichst auf 1,5°C zu begrenzen, entsprechen die derzeitigen nationalen Verpflichtungen und Emissionstrends nicht diesem Ziel. Die meisten Prognosen gehen davon aus, dass die Erwärmung bis zum Ende des Jahrhunderts zwischen 2°C und 3°C liegen wird. Darüber hinaus wächst die Besorgnis über das mögliche Überschreiten verschiedener Kipppunkte im Klimasystem: Wissenschaftler*innen befürchten den Zusammenbruch der atlantischen merodionalen Umwälzzirkulation (AMOC) (Van Westen et al., 2024), das irreversible Auftauen und Schmelzen der grönländischen und antarktischen Eisschilde (Armstrong McKay et al., 2022) sowie den Niedergang des Amazonas-Regenwaldes (Lovejoy & Nobre, 2018). Gleichzeitig ist die Frage des Klimawandels mit zunehmend schwer lösbaren Problemen behaftet. Können die Klimaziele des Pariser Abkommens überhaupt erreicht werden? Auf welche Weise kann eine Erwärmung von 1,5°C oder gar 2°C angesichts der Anforderungen der derzeitigen sozioökonomischen und politischen Systeme noch bewältigt werden? Wie massiv werden die notwendigen raschen Veränderungen des Lebensstils, der Mobilität und der wirtschaftlichen Produktion sein? Wie ist hingegen die Hebelwirkung technologischer Durchbrüche bei der Energieerzeugung, der Energiespeicherung und Klimatechnologien bei der Entgegenwirkung der Umweltzerstörung einzuschätzen?

Vor dem Hintergrund dieser hochbrisanten politischen Fragestellungen ist eine Reihe von wissenschaftlichen und technologischen Vorschlägen erdacht worden, die historisch als „Geoengineering“ bezeichnet werden und als mögliche Lösung in den Blick geraten. Ungeachtet der weitaus breiteren und komplexeren Begriffsgeschichte wird Geoengineering in den letzten Jahren synonym mit der Definition der Royal Society aus dem Jahr 2009 verwendet, die Geoengineering als „absichtliche, groß angelegte Manipulation der planetarischen Umwelt, um dem anthropogenen Klimawandel entgegenzuwirken“ versteht. Solche Ansätze verfolgen die bewusste Veränderung der geologischen, atmosphärischen und bioökologischen Systeme des Planeten, um die Klimaerwärmung auszugleichen. In diesem Sinne werden Geoengineering-Technologien als ein möglicher, zusätzlicher Ansatz diskutiert, um die Zukunft der Menschheit und der biologischen Vielfalt auf der Erde zu sichern, indem sie Schäden des Klimawandels durch groß angelegte Umwelteingriffe möglicherweise begrenzen. Die Entnahme von Kohlendioxid aus der freien Atmosphäre, die so genannte Kohlenstoffdioxid-Entnahme (CDR), könnte zur Senkung der Kohlenstoffkonzentration beitragen und so den Treibhauseffekt und die entsprechenden Klimaauswirkungen verringern. Wenn diese Art der Bekämpfung der eigentlichen Ursache der Klimaerwärmung nicht ausreicht, könnte eine ‚brachialere‘ Form des Eingreifens in das Klima die globalen Temperaturen künstlich senken, indem das Reflexionsvermögen (die sogenannte Albedo) der Erde erhöht wird - ein Ansatz, der als Modifikation der Sonnenstrahlung (SRM) bezeichnet wird. Zahlreichen Akteur*innen aus Wissenschaft, Zivilgesellschaft und Politik erscheint Geoengineering jedoch keineswegs als mögliche Lösung oder wünschenswerter Ansatz. Sie befürchten vielmehr eine Verschärfung des Grundproblems durch Geoengineering-Technologien, da diese technologischen Vorschläge zu Verzögerungen bei der Emissionsreduktion, zu Greenwashing oder sogar zur Intensivierung der Gewinnung von fossilen Rohstoffen führen könnten. Auch wenn es verlockend ist, Geoengineering als einen für die Sorgen über den Klimawandel passgenau zugeschnittenen Ansatz zu betrachten, tangieren diese technologischen Ansätze in Wirklichkeit viele politische und soziale Anliegen und greifen in geophysikalische, atmosphärische und bioökologische Prozesse ein.

Die Frage des Geoengineerings wird im Gesamtkontext einer von Zielen geleiteten Klima- und Nachhaltigkeitspolitik ausgehandelt werden, die unter anderem durch den Referenzrahmen der Sustainable Development Goals (SDGs) der Vereinten Nationen geprägt ist. Die 2015 beschlossenen SDGs zielen darauf ab, bis 2030 eine weltweit nachhaltige Entwicklung unter Beteiligung aller Mitgliedsstaaten der Vereinten Nationen zu erreichen. Diese Ziele decken ein breites Spektrum an sozioökonomischen Vorgaben ab, während gleichzeitig der Klimaschutz und die Erhaltung der biologischen Vielfalt betont werden. Vorschläge zum Geoengineering überschneiden sich mit solchen politischen Zielen und werden von ähnlichen politischen Kräften beeinflusst.

Dieser Bericht umreißt die wichtigsten Fragen rund um Geoengineering-Technologien - sowohl CDR als auch SRM -, beleuchtet ihre technischen und ökologischen Komponenten und verankert sie im Kontext einer von Zielen geleiteten Klima- und Nachhaltigkeitspolitik. Auf dieser Grundlage enthält der Bericht mehrere Handlungsempfehlungen für die Politik. Zu den wichtigsten Empfehlungen und Erkenntnissen gehören:

- Weder SRM noch CDR können eine Alternative zur schnellen **Dekarbonisierung** darstellen. Die Aussage, dass CDR genutzt werden kann, um verbleibende Emissionen zu kompensieren, ist - mit der einzigen Ausnahme von eng umgrenzten schwer vermeidbaren Emissionen – problematisch. Aussagen, die nahelegen, dass SRM – aus welchen Gründen auch immer – als Grund für eine Bremsung des Klimaschutzes verwendet werden könnte, sollten aktiv zurückgewiesen werden.
- **Governance-Risiken** sind ein zentrales Anliegen für alle Geoengineering-Technologien. Abgesehen von der Frage der Verzögerung der Emissionsreduktion, der Verantwortung (diffus oder zentral organisiert, direktiv oder marktorientiert), geht es auch um die Zukunftssicherheit der Governance-Verfahren, um Fragen der künftigen Stabilität und Governance sowohl der Kohlenstoffentnahme und -senken als auch der SRM-Verfahren.
- Bestehende Modellprojektionen können sowohl für SRM als auch für CDR **zu optimistisch** sein, da viele Projektionen von einer geordneten, vereinbarten und wirtschaftlich optimalen Umsetzung ausgehen. In der politischen Realität scheint eine solche optimierte Umsetzung unwahrscheinlich.
- Das **Potenzial** für CDR bleibt höchst ungewiss, wobei die Schätzungen der Kosten und des Umfangs stark variieren.
- **Die ökologischen Folgen, die soziale Umsetzbarkeit, die Akzeptanz und die Gerechtigkeit** von CDR-Methoden müssen baldmöglichst in die Bewertungsverfahren und in politische Prognosen einbezogen werden. Solche Überlegungen werden sich unweigerlich auf den Umfang und das Ausmaß des CDR-Potenzials auswirken.
- Obwohl die **SDGs** als ein gutes Abbild global politisch vereinbarter Prioritäten dienen, ist es **unwahrscheinlich**, dass eine **direkte Bewertung von CDR oder SRM** anhand dieser Ziele ein **ausreichend umfassendes Verständnis** der politischen Wünschbarkeit oder der Umweltfolgen dieser Technologien liefert.
- Die derzeitigen **politischen und wissenschaftlichen Praktiken**, einschließlich politischer Zeit- und Zielvorgaben, können die unbeabsichtigte Folge haben, dass Geoengineering-Technologien - sowohl CDR als auch SRM **- ohne ausreichende demokratische oder politische Abwägung** ins Blickfeld gerückt werden.

- SRM-Technologien, die der Erwärmung auf globaler Ebene entgegenwirken sollen, sind **äußerst riskant und unsicher**; gravierende negative Auswirkungen und Kosten wären hinzunehmen. Darüber hinaus geht SRM nicht auf schädliche Auswirkungen des Klimawandels ein, die nicht direkt mit der Erwärmung zusammenhängen, so z. B. die Versauerung der Ozeane.
- **Die Entscheidungsfindung im Zusammenhang mit SRM** wird nur schwer demokratisch zu bewerkstelligen sein, da sie globale Entscheidungskapazitäten, eine fundierte Zustimmung zu äußerst komplexen Fragen sowie privatwirtschaftliche und nationale Interessen erfordert. Es gibt ein **potenzielles Spannungsverhältnis zwischen der gerechten Umsetzung und nationalen (oder sogar kommerziellen) Interessen**.
- SRM kann zu Machtkämpfen und **geopolitischen Konflikten** führen. Die ungleiche Verteilung der Auswirkungen, z. B. auf Niederschlagsmuster oder das Risiko extremer Wetterereignisse, zwischen Regionen und Ländern birgt das Potenzial für geopolitische Spannungen.
- **Eine Vereinbarung, die den *Einsatz* von SRM und die Forschungspraktiken einschränkt, ist dringend erforderlich**. Die genaue Form eines solchen Nicht-Nutzungsabkommens sollte Gegenstand einer politischen Debatte sein, die zumindest teilweise von sozialwissenschaftlicher Expertise geleitet wird.

1 Introduction

Climate change is an increasingly urgent problem. Although the Paris Agreement signalled a commitment to a climate target of 2°C, or even 1.5°C, current national commitments and emissions trends do not track with these targets. Most projections projections place end-of-century warming somewhere between 2°C and 3°C. Moreover, concerns over the possible crossing of various tipping points in the climate system also intensify, with scientists fearing the collapse of the Atlantic merodional overturning circulation (AMOC) (Van Westen et al., 2024), irreversible melting of the Greenland and Antarctic ice sheets (Armstrong McKay et al., 2022), or the collapse of the Amazon rainforest (Lovejoy & Nobre, 2018). Yet at the same time, the question of climate change is beset by evermore intractable concerns: Can the climate targets of the Paris Agreement even be met? In which ways can a warming 1.5°C or even 2°C still be achieved given the demands of current socioeconomic and political systems? How drastic will the necessary rapid changes in lifestyle, mobility and economic production be? On the other hand, what is the leverage effect of technological breakthroughs in energy generation, energy storage and climate technologies in counteracting environmental degradation?

Against the backdrop of these highly charged political issues, a series of scientific and technological proposals have been conceived, which have historically been referred to as 'geoengineering' and are now being considered as a possible solution. Although the term has a much broader and more complicated history, geoengineering in recent years has become synonomous with the Royal Society's 2009 definition, "deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change". Such approaches envision the deliberate manipulation of planetary geological, atmospheric, and bioecological systems to countercool the planet. In that sense, geoengineering technologies ostensibly appear as a potential approach to safeguard the future of humanity and biodiversity on Earth. Through large-scale environmental interventions, geoengineering could, potentially, limit the damages wrought by climate change.

Geoengineering is an umbrella term for two categories: Carbon dioxide removal (CDR) seeks to lower atmospheric CO_2 levels, lessening the greenhouse effect and corresponding climate effects. Additionally, a more invasive form of climate intervention may artificially lower global temperatures, by enhancing the reflectivity (also known as albedo) of the Earth, in an approach called solar radiation modification (SRM). However, to many, such geoengineering technologies do not appear as a potential solution or desirable approach at all. Rather, many fear, geoengineering technologies only risk to exacerbate the problem, as such technological proposals might lead to mitigation delays, greenwashing, or even the intensification of extractive practices. Moreover, while an isolated view on geoengineering as an approach tailored to concerns about climate change is tempting, in reality these technological approaches intersect with multiple political and social concerns as well as many geophysical, atmospheric, and bioecological processes. In political reality, it is unlikely that decisions on geoengineering technologies will be taken solely for climate purposes. Instead, these decisions will intermingle with geopolitical, economic, and potentially even military aims. Fossil fuel companies, for instance, have already portrayed carbon dioxide removal technologies as their 'social license to operate'.

As such, geoengineering has to be addressed as part of the broader realities of environmental politics. Geoengineering proposals both intersect with stated political targets and aims – like the United Nations Sustainable Development Goals (SDGs) – and are subject to similar political forces that influence environmental politics at large. For better or worse – and the jury still seems to be out on that question – the question of geoengineering will appear within the larger context of a target-driven climate and sustainability politics, as well as in the framework of geopolitical pressures that condition decision-making. Political, commercial and scientific interests also take shape within these frameworks. In this report, we explore the interplay between climate targets, SDGs, and geoengineering. We address the potential effects specific technological approaches might have on the political aims and targets expressed by the SDGs. Inversely, we further explore the crucial question, how climate targets and SDGs might affect decision-making and research on geoengineering, including both CDR and SRM. While both climate targets and the SDGs potentially provide safeguards against the rushed implementation of these technologies, they also play a role in normalising speculative technological interventions. In this report, we advice on both these aspects. In that light, this report also highlights the need to evaluate the relationship between the political focus on climate, temperature, CO_2, and geoengineering technologies. Additionally, we observe a tension between the SDGs' potential to genuinely address political sustainability concerns and their potential to be exploited as ‘empty targets’ or even greenwashing, thereby locking in geoengineering measures. Ultimately, the questions of geoengineering are therefore *political* rather than purely scientific, technological, or even regulatory.

In this report, we contextualise the question of geoengineering politically, painting the risks and potential of geoengineering technologies, both CDR and SRM, in a geophysical and political context. To do so, the report first shortly introduces the idea of geoengineering as a potential approach to anthropogenic climate change, providing an introduction of CDR and SRM respectively. Further, the report contextualises the question of geoengineering technologies in light of the SDGs and climate targets. From this introduction, we delve into the unique strengths and weaknesses of CDR and SRM. Acknowledging the political reality of a (perceived) need for CDR, the report asks *what* CDR might contribute to sustainable and responsible climate governance – and how it they might do so. Furthermore, turning to the more controversial SRM technologies, the report asks *whether* SRM could contribute to responsible climate governance at all – and if so, how.

Finally, a note on terminology, definitional work, and the context of this report. The report is the final output of the research project *ReFoPlan 2021, Geoengineering: Mögliche Synergien und Effekte mit den Sustainable Development Goals*, a collaboration between the German Environment Agency (Umweltbundesamt, UBA) and the Copernicus Institute of Sustainable Development at Utrecht University. Its findings are informed by four expert workshops on the scientific questions of SRM and CDR technologies, a governance workshop on the question of SRM, as well as numerous conversations with experts, scientists, and policymakers over the course the project. Since the last German Environment Agency position paper on geoengineering, in 2011, the term has lost some of its luster. Increasingly, debates on geoengineering technologies centre on more specialised sets of technologies, most notably (SRM) and (CDR) specifically, or even singular technologies themselves. There is merit to this specialisation, as the respective technologies have different aims, technological risks, and prospective roles in the climate politics. Nonetheless, given the family resemblance of these technologies and their potentially entangled roles in climate policy, this report still treats these technologies together, adhering to the uneasy pairing of SRM and CDR. A final caveat: in its treatment of the risks and potential of specific technologies, this report draws on two previously published reports, one on a technical expert discussion on SRM and another on a workshop on the Global Governance of SRM, as well as on two reports on technical expert discussions on both, tCDR and mCDR (s. Annex B & C). Some overlap exists between these sections of the report. The contextualisation provided here is new. Importantly, while informed by this project, the assessments, assertions, and recommendations expressed in this report represent a synthesis made by the authors, not the position of the German Environment Agency.

2 Geoengineering in Brief

The term geoengineering is an umbrella term, connoting a wide range of diverging technologies and interventions. Politically, ‘geoengineering’ is a highly contested category. In this report, we recognise this differentiation, acknowledging both the inevitable imperfection and necessity of classifying geoengineering. For many civil society organisations and scholars alike, such technological approaches risk distracting from the need to change consumption and production patterns across the globe. Moreover, as is outlined below, these technologies bring a range of major risks and uncertainties, none of which might be fully solveable in the case of large-scale implementation. Observing such family resemblances between CDR and SRM – mostly in terms of their imagined role in climate politics and shared fears of mitigation deterrence – this report adheres to the earlier classifications made by the UBA. However, for the most part, we treat CDR and SRM as the separate proposals they are, each coming into view through their own technological proposals and each carrying their own potential contributions and risks. In this section, we briefly introduce key consideration and characteristics of SRM and CDR, respectively.

2.1 Carbon Dioxide Removal

Carbon Dioxide Removal (also referred to as negative emissions technologies and greenhouse gas removal) describes a range of measures and technology proposals designed to counteract anthropogenic climate change by removing carbon dioxide from the atmosphere. By removing carbon dioxide on a large scale, its overall concentration in the atmosphere could be lowered, resulting in less global warming. Typically, these technologies are considered complementary to conventional emission reduction measures. Often, CDR technologies are divided into three areas (natural or terrestrial, engineered, and marine CDR). Terrestrial and engineered CDR (tCDR) methods include bioenergy with carbon capture and storage (BECCS), direct air capture (DAC), biochar, modified weathering or enhanced weathering, and, by some classifications, afforestation and reforestation. Marine CDR (mCDR)methods, on the other hand, include (coastal) wetland restoration (blue carbon), alkalinization, artificial upwelling, and ocean iron fertilization. It is important to note that these classifications are imperfect and other subdivisions are conceivable. Many proposed technologies capture carbon via biological or industrial processes on land and store them in or under the sea, and vice versa.

The basic assumption of CDR is that anthropogenic activities can remove CO_2 from the atmosphere and permanently store it in geologic, terrestrial, or oceanic reservoirs. Potentially, CO_2 could even be stored in products through carbon capture and utilization (CCUS), although the overall gain would be limited. All IPCC pathways rely on CDR to offset at least so-called hard-to-avoid emissions. Most also rely on carbon budget overshoot offsets. With 2023 as a base year, the remaining carbon budget to stay below 1.5°C (50% likelihood) is estimated at about 250 gigatons (Gt) of CO_2 emissions while for the 2°C target, the remaining budget would be about 1150 Gt (50% likelihood, Forster et al., 2023). At the current rate of CO2-equivalent emissions of about 57.4 GtC02e per year (United Nations Environment Programme, 2023), the remaining carbon budget for the 1.5°C target in particular might be exhausted rapidly.

CDR is controversial and uncertain. Significant questions remain about the overall potential of CDR technologies (European Academies Science Advisory Council, 2018; IPCC, 2022b; Luderer et al., 2021). Similarly, their economic costs of CDR could be prohibitive (Fuss et al., 2018). In addition to questions about cost and potential, terrestrial CDR also poses major political and social risks. Many observers have expressed concerns: the risk of mitigation deterrence (Beck & Mahony, 2018; Beck & Oomen, 2021), land grabbing, and equity concerns (Honegger et al., 2018). In addition, land-based CDR methods may also have positive and negative impacts on the environment, ecology, and hydrology (IPCC, 2022b, 2022a). The exact impacts of CDR technologies are, however, highly context-specific.

From expert workshops held by the Project Team in 2022 (s. Annex B &C), it appeared that the attending experts signal a need for clear and robust governance and assessment procedures for CDR. Key necessities for assessment and governance signalled the following:

- The **assumptions** underlying the projections and assessments of CDR potentials and climate policy need to be considered very carefully. For example, the **assumptions** made about the amount of released land from agriculture will deeply affect the **potential of land-based CDR**. Likewise, assumptions about enhanced weathering centre around the percentage of agricultural land that minerals could be applied to, the provision of the mining infrastructure, as well as **saturation effects**. Whether or not saturation effects are considered in models has critical implications for evaluating the potential of CDR technologies. Likewise, many CDR methods also require significant energy usage.
- For mCDR, supreme care is likewise needed. While the ocean potentially provides a major carbon sink, the exact extent to which this capacity can be wielded safely, responsibility, and at scale remains uncertain.
- Ecological consequences, social feasibility, acceptance, and justice of CDR methods will need to be incorporated in assessment procedures and in policy projections, covering the whole life cycle. Such considerations will inevitably affect the scope and scale of CDR potential.
- **Clear definitions and governance procedures** around accounting for mitigation in relation to CDR are necessary. Several experts argued for an accounting system that separates CDR from mitigation, to ensure that carbon accounting does not allow CDR to compensate for relatively easily abated emissions.
- **Governance risks** also need to be considered. Beyond questions of mitigation deterrence, questions of responsibility (diffuse or centrally organised, directive or market-based), such questions include **future-proofing** governance procedures, addressing questions around the future stability and governance of both carbon capture and carbon sinks.

What we don't know about CDR at large

CDR is a necessary domain of research and development, yet one fraught with complications. It is not at all clear what potential of different technologies are, nor how they interact with one another. The estimates for many technologies vary by an order of magnitude or more, even when accounting only for geophysical, bioecological, and technical constraints. When economic considerations and social, political, and justice issues enter the equation such uncertainties compound further. In any case, it is unlikely that CDR technologies will reach the optimistic potentials as they appear in assessment reports. Even more uncertain is whether they will reach the potential that is assumed in many climate-emissions projections based on integrated assessment modelling (IAM) and corresponding national climate policies. As a recent investigation by Lisette van Beek and colleagues (van Beek et al, 2022) found, many IAM modellers themselves are deeply sceptical about the potential of real-world climate policy to achieve the CDR potentials their models assume.

2.2 Solar Radiation Modification

In light of increasing concerns that even the combination between mitigation and CDR will not provide sufficient safeguards for the climate's future, solar radiation modification has become an increasingly central concern for both climate science and climate politics in recent years. As mitigation so far proves elusive, a growing number of climate scientists points to a perceived potential need for SRM. However, SRM remains *deeply* uncertain and – as most researchers concerned agree – a majority of the envisioned technologies remains deeply undesirable on the face of it (Bellamy et al., 2016; Sovacool et al., 2022). The assessment of the U.S. National Academic of Sciences, Engineering, and Medicine (NAS) indicated last year that SRM technologies might *potentially* offer an additional strategy for responding to climate change – although this is highly uncertain. At the same time, it can never be a substitute for reducing GHG emissions: "This is in part because [SRM]

- does not address the underlying driver of climate change (increasing GHG concentrations in the atmosphere) or the key impacts of rising atmospheric CO_2 such as ocean acidification;
- raises concerns about new risks, uncertainties, and unintended impacts on natural ecosystems, agriculture, human health, and other critical areas of concern for society;
- cannot provide a reliable means to restore global or regional climate to some desired prior state; and
- entails unacceptable risks of catastrophically rapid warming if the intervention were ever terminated (if it were used to offset a large amount of warming without simultaneously deploying measures to reduce GHG emissions)" (National Academies of Sciences, 2021: p. 2-4).

Technically and climatologically, there are questions about the efficacy of SRM at large scales and the potential for unwanted effects. Such questions apply for SRM as a broad category, such as concerns over precipitation patterns or attribution of effects to specific SRM interventions. Specific technologies also present specific risks and uncertainties. For SAI, for example, these include effects on hydrological cycles (Cheng et al. 2019; Tilmes et al. 2013) and on stratospheric ozone (Tilmes et al. 2021, 2022), as well as its regional and seasonal effects (Abiodun et al. 2021; Krishnamohan/Bala 2022; Visioni et al. 2020). Additionally, there are concerns about knowledge production. The reliability and validity of model-based projections, on the one hand, are debated (Fasullo/Richter 2022). Field experiments, on the other, are deeply controversial (Mettiäinen et al. 2022). Finally, social and political concerns about SRM raise questions about whether SAI could be governed fairly and democratically (Grieger et al. 2019; McLaren/Corry 2021a).

In short, as recognised in the more technical report on SRM and its uncertainties (Oomen & Niesen, 2024), this is a deeply controversial field of research, with the potential use of these technologies being highly uncertain and potentially dangerous. Moreover, the thorniest issues with SRM are undoubtedly questions of geopolitics, governance, and justice. As such, the key findings to recognise are:

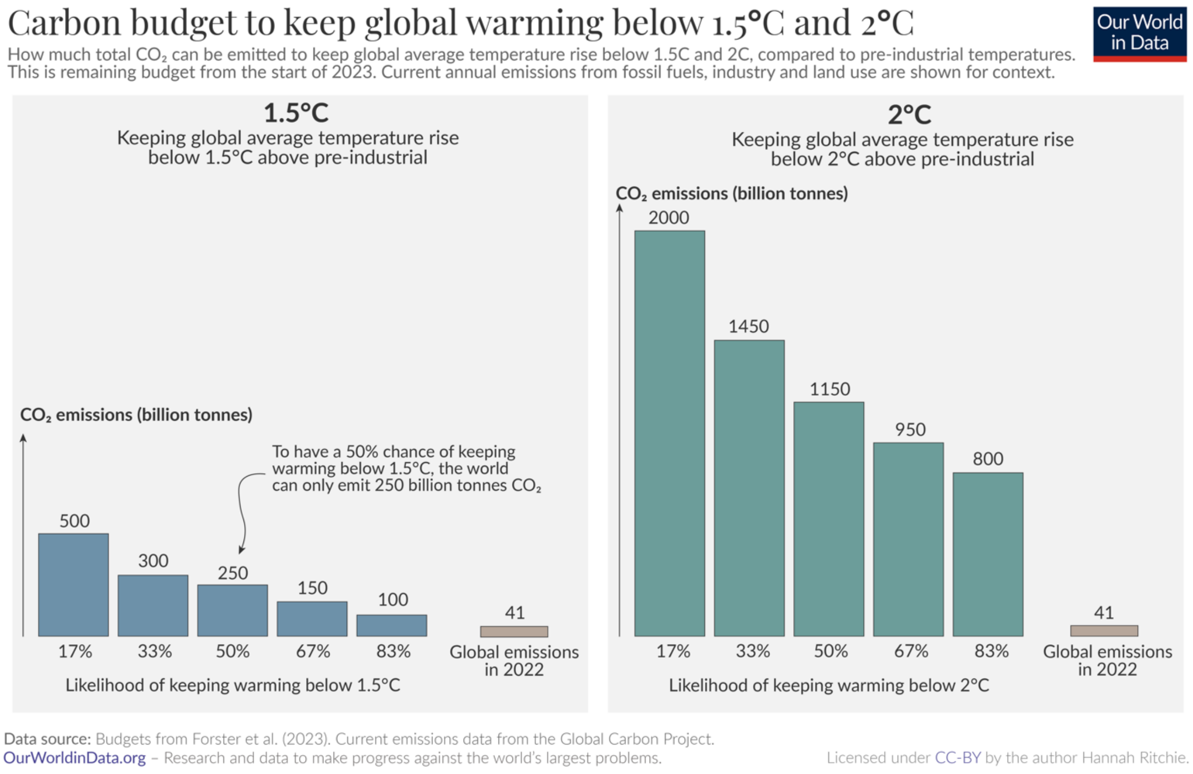
- SRM is **not an alternative** for rapid and complete decarbonization. It cannot substitute conventional emission reduction and mitigation. SRM could potentially **mask** warming but does not address the cause of global warming and **cannot reverse** global warming perfectly.

- SRM technologies aimed to counteract warming on a global scale are **highly risky and uncertain**. Moreover, SRM does not address detrimental effects of climate change beyond those directly related to warming. For example, it does not address serious impacts such as ocean acidification.
- **SAI may deter from mitigation policies:** Political actors might be tempted to argue for SRM options in order to present solutions and promising activities to avoid unpopular emission reductions or expensive climate adaptation measures. This process may also happen inadvertently.
- **Decision-making around SRM** requires global decision-making capacity, informed consent over deeply complex issues, and private and national interests to ensure a just implementation and meet standards of accountability and transparency. This demand may conflict with national or even commercial interests.SRM may lead to power struggles and **geopolitical conflict**. The uneven distribution of impacts, e.g., on precipitation patterns or the risk of extreme weather events between regions and countries holds the potential for geopolitical tensions.
- **A non-use agreement** banning the *use* of SRM and governing research practices is urgently necessary. The exact form of such a non-use agreement should be subject to political debate, led at least in part by expertise in the social sciences.
- Many **justice concerns** exist around implementation, research, and mitigation politics**.**
- Existing SRM model projections may be **overly optimistic** about SRM, as most model runs assume that SRM would be implemented in ways that are roughly optimised and agreed upon. In political reality, such an optimised implementation seems unlikely.

3 Geoengineering in Context: SRM and CDR

The background to the surge of interest in geoengineering technologies are escalating fears about anthropogenic climate change. With 2023 as a base year, the remaining carbon budget to stay below 1.5°C (50% likelihood) is estimated at about 250 gigatons (Gt) of CO_2 emissions (50% likelihood, Forster et al., 2023; also s. the introduction into this topic by UBA). At the current rate of CO2-equivalent emissions of about 57.4 GtC02e per year (United Nations Environment Programme, 2023), the remaining carbon budget might be exhausted rapidly. The IPCC is crystal clear in its AR6 Synthesis Report: rapid emission cuts are necessary, with global net emissions of $C0_2$ almost *halving* by 2030 and decreasing to zero by 2050, in order to reach the 1.5°C target (IPCC, 2023). With emissions cuts failing to materialise at the pace needed, both climate targets are in doubt. Although every increment of mitigation matters, this paints a dire picture for the future of the climate.

Figure 1: Carbon Budget



Source: OurWorldinData, based on Forster et al., 2023.

Geoengineering technologies ostensibly appear in this emissions gap, as a potential complement to conventional mitigation. However, the history of geoengineering is more complex. The term geoengineering encompasses a wide range of diverging technologies and interventions, historically connoting a wide range of large-scale interventions in the planetary environment. It is used widely both in relation to anthropogenic climate change (e.g. National Academies of Sciences, 2021; National Academy of the Sciences, 1992; Royal Society, 2009; German Environment Agency, 2011) and lithosphere geoengineering (e.g. Civil Engineering Research Foundation [CERF], 1994; Morgenstern, 2000; National Research Council, 2006, p. 1), as well as occasionally in ecology in relation to treating hypoxic dead zones in seas and lakes (Lürling et al. 2016; Stigebrandt et al. 2015). Although these interventions share a family resemblance in terms of the underlying rationality and aims (Oomen/Meiske 2021), in the public eye geoengineering has increasingly come to be synonymous with ‘climate (geo)engineering’. Scientific and political interest in geoengineering predates ‘climate science’ as a discipline, being as old as the scientific recognition of the link between carbon dioxide concentrations and global temperature (Baskin 2019; Fleming 2010; Oomen 2021). In relation to climate change, geoengineering technologies were among the first proposals when the issue arrived on the political agenda (The White House 1965). However, by the time climate change became a major political issue in the 1980s and the 1990s, geoengineering technologies had become controversial.

At this beginning of institutional climate politics – with the founding of the IPCC in 1988 and the UNFCCC in 1992 – both scientists and politicians viewed geoengineering technologies as dangerous distractions from necessary conventional mitigation commitments (Schubert, 2021). Although ‘geoengineering’ did make it into a prominent 1992 report on climate change by the National Academy of the Sciences, interest in geoengineering thus remained marginal until the mid-2000s, when it experienced a resurgence, notably marked by the Royal Society's 2009 report, which at the time included both carbon dioxide removal (CDR) methods and SRM. Since then, the term ‘geoengineering’ has increasingly been used along the lines of the Royal Society’s 2009 definition of the term: ‘deliberate large-scale intervention in the Earth’s climate system, in order to moderate global warming’ (Royal Society, 2009: ix). In 2011, the UBA published its own position paper on geoengineering, likewise as a broad technological category (German Environment Agency, 2011). A series of scientific and policy assessments and commitments of SRM followed suit (e.g. National Academies of Sciences, Engineering, and Medicine, 2021; National Research Council, 2015; United Nations Environment Programme, 2023; Williamson & Bodle, 2016). Recently, the European Commission and the European High Representative for Foreign Affairs jointly published a communication in which they stated the EU ‘will support international efforts to assess comprehensively the risks and uncertainties of climate interventions, including solar radiation modification’ (European Commission/High Representative of the Union for Foreign Affairs and Security Policy 2023, p. 20). Also in 2023, in June, the White House published a report including a congressionally mandated research plan focusing on atmospheric SRM methods (especially SAI and MCB). The report explicitly does not represent a policy decision by the executive branch of the Biden administration, but develops theoretical guidelines for transparent and equitable SRM research and approaches for national and international coordination (OSTP 2023).

Since 2011, much has changed in the political and scientific debate around climate change and geoengineering – although many of the same uncertainties remain. Since 2015, the uneasy pairing between CDR and SRM measures under the header of ‘geoengineering’ (or ‘climate engineering’) has dissipated. As climate change has become an increasingly urgent public and political concern, various dynamics in the science-policy interface have altered the status of geoengineering technologies.

3.1 Normalisation impact of the Paris Agreement and IPCC reports

Since the 2015 Paris Agreement, CDR has become an integral part of climate policy. Article 4 of the Paris Agreement states that in the second half of the century greenhouse gas neutralitiy should be achieved by balancing residual emissions with sinks, although there are serious disagreements and doubts about the extent to which CDR is practically and economically feasible or socially and politically desirable (IPCC, 2022). To some extent, CDR technologies are an important means by which scientists and policymakers maintain the feasibility of these climate targets (van Beek et al., 2022). Most climate policy model projections foresee heavy use of CDR in the coming decades, although criticism abounds of those underlying assumptions that make CDR technologies appear attractive and promising in models (e.g., Beck & Oomen, 2021; Carton et al, 2020). According to a 2019 report from the National Academy of Sciences, safe and efficient application of existing CDR methods could sequester up to 10 gigatons of CO2 per year by 2050, and perhaps as much as 20 Gt by 2100, although these numbers are disputed and uncertain.

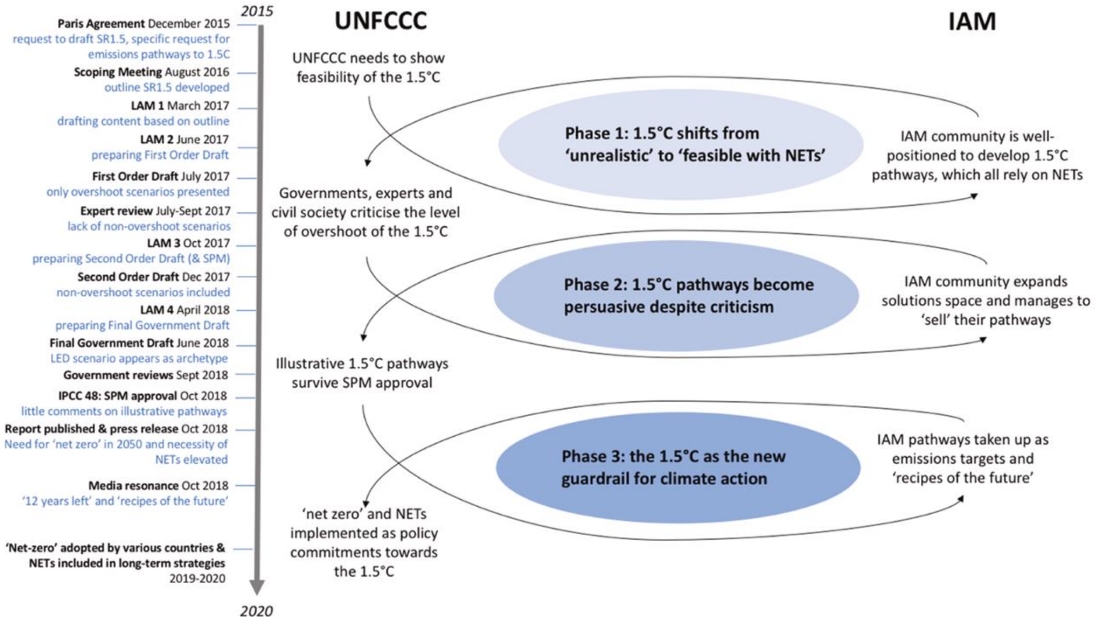
The normalisation of CDR technologies previously firmly classified as geoengineering through the Paris Agreement had several reasons. First and foremost, the agreement institutionalised concrete climate targets, targets that, according to prominent policy models, could only be achieved by removing carbon dioxide at a massive scale. Despite serious misgivings about its potential and its risks, CDR has moved into the heart of climate policy, imagined to be complementary to conventional mitigation (see chapter 4). SRM, which has not (yet) been normalised through such opaque means – and is certainly not countenanced by existing agreements – remains controversial, deeply uncertain and highly problematic. As a result, CDR and SRM have become increasingly differentiated and increasingly treated in isolation from one another, leaving the term 'geoengineering' to either a) exclusively refer to SRM (in the guise of solar geoengineering), or b) to reside in the domain of activism and civil society, as the term vanishes in policy circles, especially in relation to carbon capture technologies. Where prior to the Paris Agreement, both CDR and SRM were routinely grouped under the term geoengineering, this shifted significantly in the years after, especially following the IPCC's 2018 special report *Global Warming of 1.5°C*. In the report, the IPCC detailed the physical impacts of a global warming of 1.5°C but also, importantly, outlined emissions pathways to reach the target. By normalising CDR measures as a part of climate policy, these pathways have proven crucially important in the development of 'geoengineering' as a scientific field. When countries agreed on the 1.5°C target in Paris in 2015, it came as a surprise (Cointe & Guillemot, 2023; Livingston & Rummukainen, 2020). Prior to COP-21, no one had expected such an ambitious target to prevail. Although there had been dissatisfaction about the 2°C target among the small island nations, who argued a target of 2°C would mean their disappearance, 1.5°C was not considered to be a serious alternative. As scientific reviews of the consequences of the 2°C between 2009 and 2015 suggested that "that a 2°C danger level seemed totally inadequate" (Tschakert, 2015, p. 8), despite a dearth of scientific data available to assess lower temperature targets. Unexpectedly, however, the 1.5°C proposed by the small island states picked up steam during COP-21, leading to a final agreement that was much more ambitious than anyone expected. The problem was, however, that no one knew if this target could be reached. Prior to the COP, very little research had been done into the 1.5°C target, not even to assess the difference in the consequences between 1.5°C and 2°C (Livingston & Rummukainen, 2020; van Beek et al., 2020, 2022).

Signed and ratified by 195 parties, 194 countries and the European Union, only a few countries do not at least acknowledge the need to limit global warming to a maximum of 2°C above pre-industrial levels. Moreover, Article 4 of the Paris Agreement, which commits to achieving greenhouse gas neutrality in the latter half of the century, expressly emphasizes the utilization of carbon sinks alongside emissions reductions, with this priority reflected in the newly formed NDCs and national policies of the signatories. Although 'the jury is still out' on the efficacy of the Paris Agreement, it at least has stabilised climate change as one of the primary political concerns of the 21st century.

The IPCC's emissions pathways play a key role in maintaining the political conviction that the Paris Agreements' climate targets are still plausible and realistic (M. Beck, 2018; S. Beck & Mahony, 2018; S. Beck & Oomen, 2021). At the same time, however, they also have also played a major role in normalising so-called 'negative emissions', meaning CDR technologies, as an embedded part of climate policy. Thankfully, SRM has not been included in similar IPCC pathways yet, as it does not correspond to greenhouse gas neutrality but rather to lowering temperature. In recent years, however, the first IAM model runs including SRM have been done, narrowly framing SRM as a technoeconomic question (Harding et al., 2022). Moreover, the IPCC is currently considering to fast track parts of SRM assessment, risking a similar dynamic.

As Lisette van Beek et al. (2022) show, a complex process of political navigation and calibration in the science-policy interface after the Paris Agreement rendered CDR an eminent part of climate policy. Because most observers were unsure the 1.5°C target could be met, the UNFCCC asked the IPCC to write a special report on the 1.5°C target (SR1.5). It was a request that instigated a veritable publication run on 1.5°C, as very little research into 1.5°C as a target had been done prior to the Paris Agreement (Cointe & Guillemot, 2023; Tschakert, 2015; van Beek et al., 2022). At the heart of this research were the **integrated assessment modelling (IAM) communities that provided projections of pathways compatible with the 1.5°C target**. Effectively, these pathways were to show that the 1.5°C target was feasible in the first place. It was here that the normalisation of CDR – and its disconnection from 'geoengineering' – manifested most prominently. When the first version of the report opened for review, it presented no pathways compatible with the 1.5°C target that did not rely on significant negative emissions. In doing so, the report implicitly insisted that climate policy could not do without technologies that had been deeply controversial only a few years prior. After severe reviewer criticism, subsequent rounds of the report did include alternative pathways, including more demand-side reductions and less CDR, but the core message remained the same: CDR and negative emissions at a large scale would simply be unavoidable in climate policy. As van Beek et al (2022) recount, the process around IPCC's SR1.5 shifted the status of the 1.5°C from 'unrealistic' to 'feasible with NETs' (see figure 2).

Figure 2: The Normalisation of the 1.5° Goal



Source: Van Beek et al., 2022, p. 199.

In effect, the 1.5°C had normalised CDR as a part of climate policy. To some extent, this was a necessity to uphold the target. However, this was also the consequence of IAMs trying to model pathways to the 1.5°C goals, while operating within specific paradigms and conventions. IAM projections contain several key assumptions that limit options in the parameters of the models, which in turn render CDR both attractive within the logic of the models and necessary as other forms of mitigation seem implausible within this logic. These key assumptions include:

- *Economic growth*: IAM projections rarely question the need for economic growth, not even in affluent Western countries. In fact, as Tejal Kanitkar and colleagues (Kanitkar et al., 2022, 2024) show, IPCC projections assume *a higher absolute* consumption and GDP growth in affluent countries than in less affluent countries. In terms of mitigation, too, they assume far more continued emissions in the West than in other parts of the world.
- *Linear technological development*: within the logic of the models, technologies will get cheaper and better developed in a linear fashion. However, in practice this assumption simultaneously seems to underestimate the exponential development of renewable energy and the consistent high price of CDR (Way et al., 2022).
- *Discount rate*: IAM models include a discount rate, a mathematical device comparing costs in the future with those in the present. Using a discount rate, costs in the future rate lower than those in the present. Combined with the assumption of linear technological development and economic growth, this discount rate risks suggesting that it is cheaper to mitigate using CDR in the future than cutting emissions in the present.
- *Cost-optimal mitigation:* IAMs assume that mitigation will take place where and when it is cheapest to do so. As a result, an outsized mitigation and CDR burden is placed on poorer countries, especially when it comes to land-based CDR. As land in poorer countries is cheaper and often more sparcely populated, such countries have more 'marginal lands' that may be used for tCDR (see above) (Carton et al., 2020a; Rubiano Rivadeneira & Carton, 2022).
- *Absence of justice considerations:* IAMs, finally, do not take into account considerations of justice. In their Equity Assessment of the IPCC's 6th assessment report, Kanitkar et al. (Kanitkar et al., 2024) project that this leads to highly inequal outcomes in which a relatively high mitigation and CDR burden is placed on poorer countries.

In sum, the Paris Agreement's effects have created new conventions for climate policy. On the one hand, its target have set nearly all political decision-making in sharp relief against the need to cut emissions urgently. On the other hand, however, it has worked to normalize CDR in ways that were neither inevitable nor deeply considered. Instead, this normalization was a feature of the way in which the science-policy interface operated. While this development might not devalue CDR altogether – it may well be needed at scale – it does caution against overly optimistic assumptions about the potential of CDR. Moreover, such a process of rapid normalization, without much critical scrutiny, also raises questions for the ways in which SRM will be embedded in climate politics in the future. Crucially, it raises the question: can our current political processes around geoengineering safeguard sustainability goals? And what does that mean for those goals?

4 Geoengineering in the Context of the SDGs

Geoengineering technologies explicitly come into view through concerns about anthropogenic climate change. However, as their impacts intersect with myriad other political considerations, it is important to take a broader view on these technologies. Rather than simply asking the question whether geoengineering technologies might help accomplish climate targets – which, in their focus on temperature can be misleading and have steering effect (see section 4) – connections to issues such as biodiversity, modes of decision-making, food security, and economic factors as well as potential geopolitical tensions should be addressed and taken seriously. The most comprehensive, politically-agreed upon framework aimed at bringing such diverse perspectives together is the Sustainable Development Goals (SDGs) Framework.

Adopted in 2015, the SDGs are seventeen politically agreed upon political goals for 2030. With all United Nations member states endorsing them, the SDGs aim to provide "a shared blueprint for peace and prosperity for people and the planet, now and into the future". The SDGs are wide-ranging. Their targets include human-centred goals such as the elimination of poverty (SDG 1), zero hunger, and good health and well-being (SDG 3), as well as quality education (SDG 4). They also describe economical aims, such as those of decent work and economic growth (SDG 8) and industry, innovation, and infrastructure (SDG 9). Finally, they include a series of goals that aim to bring human societies, their modes of living, and their consumptions patterns in line with the carrying capacity of planetary systems. These goals include climate action (SDG 13) and biodiversity, with goals on both life below water and life on land (SDGs 14 and 15, respectively).

Figure 3: An Overview of the 17 SDGs

Source: https://www.un.org/sustainabledevelopment/news/communications-material/.

When posed in light of the Sustainable Development Goals, the question of CDR and SRM becomes even more complicated. Although both CDR and SRM originate in the climate debate, it is clear that they will interact with the SDGs in complex and unpredictable ways. The impacts of climate change (SDG 13) influence all the other SDGs, as climate change threatens biodiversity, food security, and the access to clean drinking water. Additionally, the destabilising effects of climate change also potentially affect political stability, inequalities, gender equality, and educational opportunities. As such, geoengineering technologies, whether SRM or CDR, also potentially intersect with all of these concerns too. Importantly, however, these intersections are not straightforward, as the few assessments on the relationship between the SDGs and geoengineering technologies make clear. Conceivably, regionalised forms of SRM, such as marine cloud brightening (MCB), might be employed in an attempt to safeguard the Great Barrier Reef from overheating, as a research project is already investigating. In doing so, marine cloud brightening is supposed to help safeguard life below water (SDG 14). Likewise, a deployment of either CDR and SRM that succeeds in minimising climate risks would prevent untold economic damage, human suffering, and would limit biodiversity loss and the loss of clean water. On the other hand, both CDR and SRM might also have severe detrimental effects on political targets, as they might disrupt ecosystems, prove expensive or unreliable, or might lead to political conflict. Moreover, a 'termination shock' following the abrupt cessation of SRM, leading to rapid increase of temperature, could potentially lead to severe disruptions, threatening all SDGs.

Scientific assessments of these relationship diverge widely in their conclusions about the relationship between the SDGs and geoengineering technologies. Although there is a general consensus about the potential for significant interactions, the jury is still out on whether these interactions will be (mostly) positive, (mostly) negative, or mixed. According to Linda Schneider, for instance, "both Carbon Dioxide Removal and Solar Radiation Management schemes are bound to exacerbate concomitant socio-ecological and socio-economic global crises, deepen societal dependence on technocratic elites and large-scale technological systems and create new spaces for profit and power for new and old economic elites" (Schneider, 2019, p. 29). As a result of this further centralisation and entrenchment of power and profit, Schneider fears that geoengineering threatens to undermine the achievement of both the SDGs and ambitious climate action. As Enevoldsen et al. (2022) observe based on solliciting 125 experts, such fears are widely shared by experts. However, many experts also insist geoengineering technologies could help reach SDGs. According to their expert interviews, CDR „deployment could enhance the attainment of 16 of the 17 SDGs, but this comes with possible tradeoffs with 12 of the SDGs. SRM deployment could not only enhance the attainment of 16 of the 17 SDGs, but also create possible tradeoffs with (a different) 12 SDGs" (Enevoldsen et al., 2022, p. 1). By reducing extreme heatwaves, floods, droughts, and the impact on water security, the interviewed experts assert that SRM, for instance, could significantly lower risks to the SDGs. In one of the most expansive assessments of the relationship between the SDGs and geoengineering, the Carnegie Climate Governance Initiative, a thinktank investigating the potential of these technologies, observes that "research indicates that at least three quarters of the SDGs would likely be affected in some way if large-scale Carbon Removal or Solar Geoengineering were to be deployed". If, they argue, these technologies prove feasible, effective, and desirable, such "technologies might contribute to limiting the impact of climate change on the SDGs" (on website).

All three assessments mentioned above acknowledge that the impact of CDR on the SDGs is not well-understood yet. For SRM, the uncertainties are even greater, as the geophysical, technical, and political risks of these technologies are immense. In the accompanying report, the authors stress that "Deployment of Solar Geoengineering as well as large-scale Carbon Removal would be expected to have physical side-effects and socio-economic or political implications affecting the delivery of SDGs. Physical side-effects in particular relate to: land-use and food security; water quality and availability; health; energy; economic productivity; and biodiversity. Socio-economic or political implications include: economic and cultural impacts; opportunity costs;

political tensions and governance demands" (Honegger et al, 2018: 7, bold text in original). Across-technology governance challenge therefore lies in ensuring participatory and just implementation (SDGs 16, 17). Finally, the risk of mitigation deterrence has an impact on SDG 13 with its focus on urgent action to combat climate change.

Figure 4: Potential risks geoengineering to the SDGs

Source: Honegger et al., 2018.

The possible interactions between the SDGs and geoengineering are too numerous to explore in detail, but several examples of possible interactions between the SDGs and CDR can be found in the literature:

4.1.1 Possible interactions between CDR and the SDGS

- In the case of mCDR, the high energy and material expenditure in the use of macronutrients mentioned above must be critically evaluated with regard to possible environmental pollution and further CO_2 emissions and is also potentially in competition with the agricultural fertilizer industry with consequences for food security (SDG 2, Zero Hunger). (Honegger et al., 2018).
- Ocean downwelling could have positive effects through its co-benefits in combating eutrophication, while Artificial upwelling might have positive effects on fish stocks and aquaculture, which could result not only in desirable cascading effects on CO_2 sequestration, but also on food security (SDG 2) (National Academies of Sciences, 2021). However, the approach also carries risks for precipitation and ocean acidification, which could have numerous effects on the SDGs, from the affected terrestrial and marine ecosystems (SDG 14, Life below Water) to food security (SDG2) (see Annex A).

- Enhanced weathering or alkalinity enhancement processes pose health risks due to dust pollution during mineral mining (SDG3, Good Health and Well-Being). In principle, a positive effect on marine ecosystems (SDG 14) would be expected by counteracting acidification (Feng et al., 2016; Gattuso et al., 2018). However, due to possibly regionally different alkalinity increases depending on the place of application, there is a risk of substantial chemical changes in the seawater and thus for ecosystems. The risk of uneven or too rapid change could put them under additional stress (National Academies of Sciences, 2021, Bach et al., 2019).

- In addition to CO2 removal, methods of protecting and restoring marine and coastal ecosystems are generally expected to provide co-benefits for the SDGs, which include better water quality (SDG 6, Clean Water and Sanitation), flood protection for urban and local settlements, and better air quality (SDG3). Marine and terrestrial ecosystems are protected (SDG14). However, there may be trade-offs with the agricultural and aquaculture use of the areas, which could endanger local poverty and food security (SDG1, No Poverty; SDG2) and thus pose political challenges (Honegger et al., 2020).

- Potentially, given the emerging industries around CDR in particular, geoengineering technologies *themselves* might be a source of accounted economic growth, whatever that may be worth in light of escalating climate change. However, the picture of the relationship between both CDR and SRM on the one hand and the SDGs is not one to observe through rose-tinted glasses, as the industries, discourses, and political dimensions of these technologies potentially have severe detrimental consequences for the SDGs.

4.1.2 Possible interactions between SRM and the SDGs

Potentially, limiting global surface temperatures through SRM could limit climatic disruption, and as such benefit many SDGs. However, in many of those cases, this potential benefit is uncertain, while also presenting risks to those same SDGs:

- The most immediate interaction between the SDGs and SRM regards SDG13, Climate Action. Even prior to any implementation of SRM, this relation is a reason for concern, as many observers fear the prospect of SRM might lessen mitigation commitments (Enevoldsen et al., 2022; D. McLaren, 2016; Oomen, 2021; Sovacool et al., 2022).

- In terms of biodiversity, Life below Water (SDG 14) and Life on Land (SDG 15) might benefit through lessening temperature extremes and slowing general warming patterns. At the same time, through possible disruptions of precipitation patterns, unequal cooling across the globe, and, in a worst-case scenario, termination shock, SRM could also threaten biodiversity. Such threats to biodiversity are exacerbated by the risk that (the prospect of) SRM leads to mitigation deterrence. Even if SRM were to successfully lower temperatures, such mitigation deterrence could have catastrophic consequences for biodiversity, especially oceanic life. As rising carbon levels lead to ocean acidification, SDG14 could suffer significantly from mitigation deterrence, even if SRM is successful;

- SRM presents some potential benefits for SDG1 (No Poverty), SDG2 (Zero Hunger), SDG3 (Good Health and Well-being), as well as other human well-being related SDGs, through lowering temperature extremes. At the same time, again, the myriad uncertainties about SRM mean that SRM also provides risks for these SDGs, as the exact effects of SRM are uncertain and the spectre of mitigation deterrence looms here, too.

- Most observers agree that the most pivotal questions for SRM are political questions. As such, SRM introduces serious risks to SDG16: Peace, Justice, and Strong Institutions. Potentially, SRM could lead to political conflict over the control of the atmosphere, including warfare, geopolitical instability, and economic disruptions (e.g., Biermann, Oomen, et al., 2022; Corry & Kornbech, 2021; McLaren & Corry, 2020; Oomen & Niesen, 2024; Young, 2023). At the same time, if successfully and sustainably deployed SRM might limit the political uncertainties that connect to climate disruption.

In all these cases, the interaction between SRM and the SDGs is speculative, given the many uncertainties that surround the technologies. Given the scale of SRM's potential impacts, there is not a single SDG that would not potentially be impacted by SRM – for better or worse.

4.2 Difficulties assessing the relationship between SRM, CDR, and the SDGs

Importantly, the interplay between geoengineering technologies and the SDGs remains largely speculative and hard to quantify. Existing assessments of the interplay between SDGs and geoengineering technologies derive the potential impacts of geoengineering on the SDGs from the ways in which risks in the domain of particular SDGs appears in the scientific literature – or experts assessments of these risks. While these can be worthwhile mapping exercises to bring out the potential risks and benefits of geoengineering technologies, the exact impact of geoengineering technologies on the SDGs depends on a range of sociotechnical, economic, geophysical, and bioecological factors. For example, the risks of afforestation, reforestation, and BECCS to food security and poverty depend on the location, scale, and speed of their implementation, as well as the local forms of co-optation and resistance. Simultaneously, these interventions intersect with worsening climate conditions that may exacerbate food shortages. Yet at the same time, both by reducing carbon concentrations and by building the resilience of local ecosystems against droughts and heatwaves, afforestation and reforestation may also contribute to SDGs on poverty, biodiversity, and food security. As most assessment recognise, such interconnections are nearly impossible to quantify ahead of time, yet they are important take into account.

Addressing the connections between SRM and CDR on the one hand and the SDGs on the other hand in isolation of such complicating factors risks oversimplified and technocratic decision-making on the desirability, feasibility, and efficacy of these technologies. For example, the ways in which models quantify 'marginal lands' – lands on which currently no economically productive agriculture or rich biodiversity exists – deeply influences the assumptions under which land-based CDR methods are implemented (Rubiano Rivadeneira & Carton, 2022). As Rubiano Rivadeneira and Carton (2022) shows, many of the lands classified as marginal are, on closer, local inspection, not as marginal as the models assume. Instead, they are comprised of grassland crucial for certain ecosystems or lands used for subsistence farming. Large-scale implementation of CDR, in the form of BECCS, on such lands would potentially have severe consequences for biodiversity and the livelihoods of those living in these areas. As such, the interactions with SDGs should be contextualised based on (at least) the dimensions following below. Importantly, this is not an exhaustive list of criteria – which should be constructed as part of a larger project – but rather a distillation of concerns in the critical social and natural sciences in this field, which often deem the SDGs of little help for assessing SRM:

Climate change: Climate change might be the most important confounding and complicating factor in determining the effects of geoengineering. As anthropogenic climate change provides the rationale for considering such invasive technological interventions, their aim is to limit climate damages. However, given the existing uncertainties around the exact effects of climate change, as well as its interactions with geoengineering technologies, both the efficacy of CDR and its impact on people's lives remain uncertain. For example, climate change will change the availability of water in many regions, potentially changing the desirability and impacts of various CDR technologies. Afforestation, BECCS, and reforestation technologies might exacerbate such water scarcity for instance. However, forests might also stabilise ecosystems by stabilising hydrological systems and mediating local temperature extremes. As addressed above, such interconnections exist for many of the proposals – and should be addressed on a case-dependent basis. Moreover, the exact interactions between SRM technologies and the climate system remain uncertain.

Bioecological impacts and developments: Beyond the relationships between climate change and geoengineering technologies in determining the impacts on the SDGs, further questions exists on the interplay of these technologies with bioecological systems. Will SRM measures change rainfall patterns, plant growth, or agricultural productivity? Might CDR measures harm biodiversity or help to safeguard or restore it? All such questions are open, depending not only on the manner of implementation, but also on a range of further factors. Importantly, this also includes so-called nature-based CDR solutions, for which it is not self-evident that they stimulate biodiversity. Monocrop afforestation, for example, might damage biodiversity, while simultaneously helping to keep temperatures lower.

Socioeconomic factors and configurations: The effects of SRM and CDR are importantly connected to socioeconomic factors. The scientific literature on terrestrial CDR, for example, expresses concerns about 'land-grabbing', in which lands currently used by subsistence and small-scale farming are appropriated by large corporations and states for more lucrative endeavours such as BECCS (Carton et al., 2020b). Potentially, such land-grabbing leads to increasing poverty (SDG-1), decreased gender equality (SDG-5), and decreased biodiversity (SDG-14 & SDG 15). In a similar vein, SRM might potentially, in the form of cooling credits, create a commercial driver for 'cooling the Earth', despite uncertainties about the impacts of SRM remain. This, in turn, may lead to less firm mitigation commitments – and ultimately, to more climate damages. Occasionally, the first steps to such developments have already been undertaken (see Möller, 2020, 2021, for reflections on the ways that the International Standards Organisation tried to institutionalise a radiative forcing standard). CDR could, at the same time, also provide socioeconomic benefits, if governed correctly, in the form of interactions with SDG-9 (Industry, Innovation, and Infrastructure). However, it could also prove prohibitively expensive, harming other economic endeavours.

Technological and infrastructural impacts: The difficulty of assessing the impacts of geoengineering technologies on the SDGs is compounded by the fact that these technologies often necessitate large infrastructures and (in some cases) resources. The impacts of these technologies will not only come from their geophysical impacts, but also from the machinery and resources needed to keep these systems running. It is therefore crucial to take the entire life cycle into account.

Because of the circumstantial nature of the risks of SRM and CDR, connected to a plethora of different interactions, a straightforward assessment of the desirability, feasibility, safety, and consequences against the SDGs or climate targets does not seem like a worthwhile exercise (see chapter 4). In such an endeavour, the breadth of the SDGs would quickly turn the endeavour into a box-ticking exercise. This is not to say, however, that sustainability criteria for both these sets of technologies are not necessary. Below, some key variables to keep in mind in those assessments are outlined. However, it is beyond the scope of this project and report to detail the proceedings of such assessments.

4.3 Sustainability assessments of CDR

The reflections above suggest that any sustainability assessments of CDR need to define their priorities clearly. Moreover, the predominant socioeconomic and economic-optimal frameworks through which many assessments are conducted poses serious limitation for assessing the impacts of CDR. For a broader view, assessments should at least include the following criteria:

Regional ecological consequences: All CDR measures, whether tCDR or mCDR, risk having serious ecological consequences. Depending on the type of CDR employed, these consequences might differ from changes in hydrological cycles due afforestation, biodiversity loss due to monocultures, changes in the composition of marine life, and the dangers posed by CO_2 leakage from underground storage. Such assessments should also prioritise the health and lifecycles of fauna, flora, soil, and other natural systems.

Socioeconomic justice: many of the options for land-based CDR require the planting of significant swaths of land with forest or energy crops. In models, the lands used for such plantations are typically considered 'marginal', of no great immediate economic value. Some models suggest the need of a land mass the size of the entire Indian subcontinent (Smith et al., 2016). However, such marginal lands are often in use for subsistence farming or other manner of informal economies. Furthermore, issues of socioeconomic justice also extend to the question of who bears the costs for climate damages, mitigation, and the energy transition. As historical responsibility for climate change is located primarily in rich countries, whose wealth also importantly derived from colonial and post-colonial extraction (e.g. Hickel et al., 2022), the question of both compensation for the loss and damages due to climate change *and* the socioeconomic cost of the energy transition should be connected to questions about CDR justice.

Monitoring, Reporting, and Verification: for many CDR measures, it is difficult to gauge exactly how much carbon is captured and stored. Partially, this has to do with environmental and ecological factors, as accounting for the exact carbon cycles in oceans and coastal regions is tricky. This difficulty is compounded by the existing system of carbon credits that incentivises companies to artifially inflate their carbon capture. Yet without exact and reliable accounting systems, CDR cannot be made sustainable, as there will be no way to tell whether and to what extent these technologies help reduce carbon concentrations in the atmosphere – or whether they are merely a foil for greenwashing and mitigation deterrence. Therefore a valid MRV is needed.

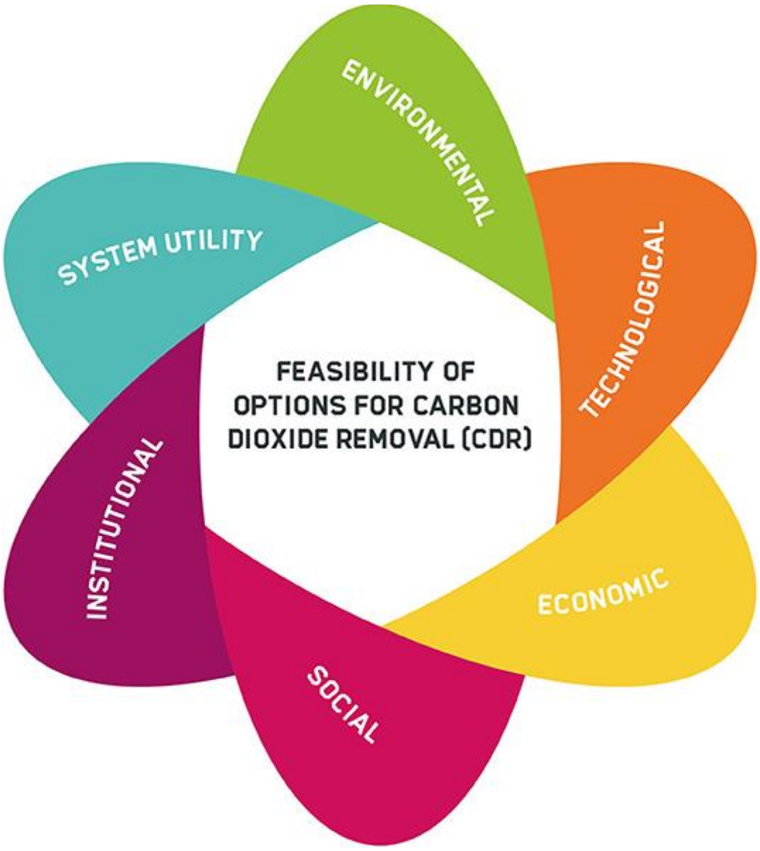
Economic affordability: various reports suggests CDR might turn out to be a prohibitively expensive endeavour, at least to make it work at the scales currently envisioned in most pathways. CDR, as an embedded part of climate policy, should be weighted against these potential costs, not only monetarily but also in terms of resource requirements and infrastructural needs. Although most current projections assume that CDR might become economically viable in the future, as its monetary costs decreases, this is not a given (Way et al., 2022). Moreover, in expert conversations, a further concern is that it may turn out to be crippling in terms of real economic, productive costs, severely costing societies the ability to safeguard the needs of their future generations.

Only compensating hard-to-abate emissions: because of the increasing normalization of CDR, the (promises of) CDR is becoming an alternative to emissions cuts, for companies and governments alike. However, given the extreme difficulty scaling CDR, as well as its socioecological concerns, CDR can only provide an alternative for hard-to-abate emissions and must not work as an offsetting mechanism for fossil emissions, that could have been avoided. However, at the moment, there is no accepted definition of residual emissions, other than questions of economic feasibility. As such, sustainably accounting for CDR needs to be set up much more carefully than is currently the case.

Safety and stability of storage: in the case of many forms of CDR, there are issues of storage. On the one hand, this uncertainty relates to the longevity of storage. Storage in products, for example, may only be temporary, or storage may be saturated. However, this uncertainty relates even more to the possibility of leakages, for example in subnautical rock formations, which could have catastrophic consequences. If CO_2 storage has no longevity, the efficacy of CDR is only temporary at best.

In recent years, there are promising indications of trend towards a broader-based sustainability assessment of CDR. For Germany, the assessment framework by Förster et al. (2022), which includes environmental, technological, economic, social, institutional and systemic implications of CDR, should be mentioned here in particular (s. figure 5). In the context of the German research landscape, the two BMBF-funded projects CDRterra and CDRmare should also be mentioned, which are focusing on land- and marine-based CDR methods, respectively, with an integrative focus, taking into account possible ecological, social, economic and legal implications. In addition to this integrative approach, it is nonetheless crucial to continue efforts towards localised case-by-case assessments in order to be able to examine specific CDR measures involving the relevant stakeholders and local conditions.

Figure 5: Overview of thematic dimensions included in the feasibility assessment framework of carbon dioxide removal (CDR) options



Source: Förster et al. 2022; UFZ/Conor Ó Beoláin, Helmholtz Climate Initiative / Julia Blenn, Creative Commons CC-BY NC 4.0 license.

4.4 Sustainability assessments of SRM

For SRM, sustainability assessments present even more difficult considerations. The exact impacts of SRM measures cannot be known ahead of time due to its interventions in exceedingly complex atmospheric and climatic systems. As such, even more so then with CDR, SRM assessments will have to be done in a projective manner. In such sustainability assessments, the following criteria should be considered:

Socioeconomic justice: Like in the case of CDR, justice considerations should be at the heart of SRM. However, the question of the connection between justice and SRM is one of the most severe disagreements in the literature. Who would control the technology? Would restrictions on SRM development be forms of neocolonialism? Is it likely that SRM will be implemented to safeguard the lives of the poor and marginalised? How will SRM impact future generations, and what responsibilities do we bear toward them in the context of intergenerational justice? These questions are subject to vehement debates. Any assessment framework should put such questions at the heart of the matter. However, these considerations are deeply complicated by other aspects of SRM.

Regional effects: It is highly likely – if not wholly unavoidable – that SRM technologies will have different regional effects. Although some modelling studies suggest that most regions might benefit from SRM (e.g. Hueholt et al., 2023; Wells et al., 2024), a definitive answer on such questions would never be available until implementation. Even after implementation the attribution of precise effects of MCB, SAI, or other SRM technologies would remain difficult (if not impossble). Moreover, especially in the case of MCB, there is a real risk of ‘teleconnections’, in which interventions in one part of the globe has significant detrimental effects elsewhere (Wan et al., 2024). As such, assessment of the potential sustainability of SRM ought to take such regional effects into account.

Permanence: A third important category of sustainability assessment for SRM should be the potential (and need) for permanence of these technologies. Barring a ‘net-negative’ future, in which emission levels drop below capture and storage levels, SRM, once implemented, would have to be maintained for more than 100 years at least (Baur et al., 2023). SRM assessments should reflect this necessity, in terms of ecological impacts, resource use, economic impacts, intergenerational justice, and the perceived sociotechnical stability of SRM infrastructures. This is especially important given the risk of a catastrophic ‘termination shock’ in the case of abrupt cessation of implemented SRM.

Economic Cost and Resource Use: Sustainability assessments for SRM should investigate the direct costs of its implementation, in terms of material costs, R&D requirements, and economic costs in a whole life cycle assessment. More importantly, however, these assessments should also include a broader, non-monetary economic assessment. Specifically, such assessments should include the resource costs of building and maintaining SRM infrastructures.

Climatic and atmospheric effects (beyond temperature): SRM risks influencing more than simply global average mean temperatures. In the scientific literature on SRM, concerns exist about SRM shifting rainfalls patterns, stratospheric circulation, stratospheric heating and other unexpected detrimental effects of SRM technologies. In the literature, these concerns are partially addressed through favouring ‘exit ramps’ and only developing reversible implementation of technologies (National Academies of Sciences, Engineering, and Medicine, 2021; Parson et al., 2024).

Effects on biodiversity: Similar concerns exist around assessing the effects on biodiversity from SRM methods. As addressed above, such effects could cut both ways – or in many different directions – as an idealised global average cooling through SRM might limit damages to biodiversity, while SRM effects on precipitation patterns might harm biodiversity. It is unlikely a clear picture of such effects would fully arise before (or even after) implementation. However, such considerations should weigh into any decision-making on SRM nonetheless. This also includes considering vegetation growth and agricultural productivity. A rapid warming after stopping the implementation could make it impossible for plants and animals to adapt, potentially leading to mass extinction.

Geopolitical Sustainability, in terms of longevity, temporal questions, and Decision-making procedures: Of crucial importance, recognised on all sides of the heated SRM debate, are good governance systems around both research and (potentially) deployment of SRM. In a recent article, Parson et al. (2024) favour harnessing the increasing normalization of SRM as a pathway towards effective assessment and governance. Biermann et al. (2022), on the other hand, argue such effective assessment and governance is difficult, if not impossible, because of the ways in which SRM entangles itself with geopolitical considerations. Despite such difference, all agree that SRM cannot be assessed, let alone deployed, without adequate governance measures.

4.5 Conclusion

Sustainability assessments for geoengineering technologies are fraught with difficulty. Although the SDGs provide a good proxy for generally agreed-upon political priorities across the globe, it is unlikely that a direct assessment of either CDR or SRM against the SDGs gives a good overview of either the political desirability or environmental impacts of these technologies. As such, separate, inter- and transdisciplinary assessment procedures should be developed. Moreover, it is important to recognise that assessments and metric can have de-facto governance effects (Gupta & Möller, 2019). As we will show in the next section, this risks effectively institutionalise, normalise, or further the development and implementation of such technologies without enough political, social, and legitimate deliberation.

5 Geoengineering in a target-driven politics

The question of the assessment, feasibility, and desirability of geoengineering technologies cannot be answered without also inverting the question about the relationship between political, climate and sustainability goals. Rather than simply ask `can geoengineering help reach the goals of the SDGs or `can CDR help reach the goals of the Paris Agreement '', the inverse is also an important question: how do these goals influence both research and decision-making on these technologies? In the nine years since the Paris Agreement and the adoption of the Sustainable Development Goals in 2015, these twinned targets have become key terms for international politics. They also have important discursive effects, as universities adopt them as guides for their curricula, municipalities frame their policies in their image, and politicians insist on their importance. Yet do they, in actuality, have the capacity to steer politics? Paradoxically, one of the main risks connecting the SDGs and geoengineering – as well as the Paris' Agreements' mitigation targets – might not be the risks that geoengineering technologies pose to the SDGs, but rather the risks that these politically agreed targets hinder sensible political decision-making around these topics. In a worst-case scenario, this even risks hurried or careless implementation of geoengineering technologies. Rather than being neutral, collectively agreed-upon goals for policy, political targets also function as a disciplining device that conditions specific forms of decision-making over others. They simultaneously rely on, reinforce, and create implicit assumptions about political priorities. As such, they are agenda-setting, often in unexpected ways. They determine what kinds of decisions and developments are deemed to be important. Such developments can be productive. Indeed, they are the point of politically agreed upon targets. They aim to alter decision-making, from multilateral agreements, national governments, all the way down to the ways in which universities are run and municipalities prioritise funding. The open question, however, remains how effective and productive such political targets are. Do they alter political decision-making? Do they steer political priorities? And do they create the most sustainable and less destructive outcomes?

The answer to these questions have far-reaching consequences for the future of both SRM and CDR. Moreover, the answers to these questions are not uniform and clearcut. Although both the Paris Agreement's greenhouse gas neutrality targets and the SDGs signal a clear political desire to address questions of unsustainability, their efficacy remains an open question (Biermann, Hickmann, et al., 2022; Bogers et al., 2022; Klees, 2024). Carbon emissions have not yet decreased, other planetary boundaries are rapidly exceeded, and most of the ecological and climatic targets increasingly seem out of reach. What, then, is the political effect of these targets? And how might they affect (responsible) decision-making on SRM and CDR? Such questions apply to both the Paris Agreement, in the form of politically agreed upon targets for mitigation and greenhouse gas neutrality, and the SDGs, in the form of defining the world's (ostensible) political priorities. This section provides some initial reflections on these questions, based on the academic literature, the expertise and experience of the authors in these fields of research, and the findings of the project "ReFoPlan 2021, Geoengineering: Mögliche Synergien und Effekte mit den Sustainable Development Goals". It presents these findings with a disclaimer, however: where not explicitly drawing on academic literature, these are interpretative findings, important considerations to keep in mind in relation to both SRM and CDR, but not definitively proven.

5.1 The impact of the SDGs

In a six-year European Research Council funded project assessing the steering effects of the SDGs, Frank Biermann and colleagues addressed the question raised above. In their assessments, Biermann et al (2022) studied evidence from over 3,000 scientific studies on the SDGs, published between 2016 and 2021. “The 17 SDGs and their 169 targets form a complex mesh of normative aspirations that seek to address all areas of human activity”, Biermann et al (2022, p. 797) write, providing a comprehensive road map for politics. Including both environmental and social targets, the SDGs in theory can be transformative. In their assessment, the authors found that “the goals have had some political impact on institutions and policies, from local to global governance“ (Biermann, Hickmann, et al., 2022, p. 795), but that this impact was “largely discursive, affecting the way actors understand and communicate about sustainable development“ (Biermann, Hickmann, et al., 2022, p. 795) and that more profound normative and legislative impact remains rare. The evidence on the SDGs’ impact on inequality, both between and within countries, for example, remains mixed. Countries might frame their policies in the context of the SDGs, but only incorporate a limited reading of inequality or do so with other strategic aims in mind.

For the purposes of CDR and SRM, of course, the key metric is the ways in which the SDGs affect climate politics and ecological integrity on a global scale. Here, the evidence, likewise, is mixed at best. Although most studies find some impact of the SDGs,

“*there is widespread doubt that the SDGs can steer societies towards more ecological integrity at the planetary scale. There is also little evidence that any normative and institutional change in this direction has materialized because of the SDGs*” (Biermann, Hickmann, et al., 2022, p. 797)

Indeed, most studies on international governance only indicate “a limited role of the SDGs in facilitating the clustering of international agreements by serving as a set of collective ‘headlines’” (Biermann, Hickmann, et al., 2022, p. 797). This lack of impact has multiple origins. For one, the breadth of the SDGs leads to a lack of focus and clarity, leaving much to be interpreted in different ways. Moreover, critical studies observe that different SDGs might conflict with each other and signal a lack of commitment (Klees, 2024). Historically, the term “sustainable development” has always suffered from being a compromise between concerns about “sustainability” and “development” (Borowy, 2014), leading the original Brundlandt report to settle on the definition “meeting the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland report, 1986). Negotiated tension between development and sustainability is still evident in the SDGs. According to critics, the SDGs remain firmly rooted in a development paradigm, privileging economic growth, framing the natural world as resources to be used for human consumption, and safeguarding nature only to conserve it for human well-being. As such, critics insist, the SDGs continue a narrow form of political decision-making that intensifies ecological crises rather than solving them. As such, the SDGs might be structurally unable to deliver the kinds of futures that they insist on.

Nonetheless, the discursive political effects of the SDGs might have serious repercussions for the decision-making on both SRM and CDR, as concerns about meeting the SDGs – as targets – may normalise, necessitate, or prohibit research and implementation of these technologies.

5.2 Target-driven politics and geoengineering

The question of decision-making about geoengineering technologies in light of stated political aims also features in climate politics proper, through the conditioning effect of the Paris Agreement. So far, the Paris Agreement has not managed to drive down emissions as rapidly as would be needed to make either the 1.5°C or 2°C climate targets, although opinions still diverge around the success or failure of the agreement. However, this is not to say that the Paris Agreement has had no impact whatsoever. Like the SDGs, the Paris climate targets have had a large discursive impact, as addressed in section 2. The bigger issue facing the debate around geoengineering, broadly defined, however, is whether the SDGs and climate targets are the right yardstick to measure these technologies by in the first place. The rapid normalisation of CDR addressed in chapter 2 should be a cautionary tale for a target-driven politics around geoengineering, whether it relies on the SDGs or on climate targets. While targets are politically important, they also have a disciplining effect on both science and policy. Rather than just being a de jure governance agreement, they also have de facto governance effects. As Aarti Gupta and Ina Möller observe, there are also "sources of governance that are unacknowledged and unrecognized as seeking to govern, even as they exercise governance effects" (Gupta & Möller, 2019, p. 481). Norms, conventions, and even convictions – like the one that CDR is necessary to make climate targets – also exercise governance effects, as they steer decision-making and influence the ways in which research is done. In the case of geoengineering, targets can contribute to "shifting the focus of governance debates from first-order 'what, if, and whether' questions to 'how, when, and who', i.e. to questions of (technical) design" (Gupta & Möller, 2019, p. 495), just as Gupta and Möller observe in the aftermath of the Royal Society (2009) report on geoengineering and its National Academy of the Sciences counterparts (National Research Council, 2015a, 2015b). In other words, the discursive linking of technologies to targets could - whether intentional or not - transform the debate on geoengineering from one of principle to one of implementation.

There is a real risk that de facto governance effects push CDR and SRM technologies into the political limelight, as they provide a means through which specific targets can still be met. However, meeting a target using dangerous, unproven, and politically contested technologies could potentially be worse than not meeting the target at all. As such, climate targets and SDGs should not be used as a metric through which to make decisions on geoengineering. This is in line with the Convention on Biological Diversity (CBD) decision X/33, which highlights the need for a precautionary approach to geoengineering, emphasizing that no climate-related geoengineering activities should proceed without a solid scientific basis and a thorough assessment of potential environmental, social, and economic impacts. Only when the risks and impacts of these technologies are sufficiently clarified according to these criteria, a tool for the integration of policy goals such as the SDGs can steer decision making. As climate targets and SDGs are an imperfect evaluation grid, reducing the complexity of geophysical, bioecological, and socioeconomic systems down to a simple metrics can lead to counterproductive policy. For example, the question of whether ever to implement technologies as invasive as SRM shouldn't be connected to whether the mitigation targets are met – neither politically in the future nor discursively in the present. They should be discussed in relation to real climate impacts, not a useful, imperfect, and politically-agreed upon proxy for these impacts. After all, it is not a given that missing politically agreed upon targets measures does not mean SRM is desirable. Even if the Earth warms 2.1°C, it may still be safer or more politically desirable to forego SRM than to deploy SRM in an attempt to lower warming to 1.5°C or even further. The inverse is also true. Even in case of 1.3°C of warming, the threat of climate tipping points might drive scientists and politicians to agree on SRM as a very last resort hoping to limit catastrophic damagess. Such decisions ought to be made on the political, scientific, and climatic merits of these interventions – not based on politically-agreed upon targets that do not clearly address the requirements, possibilities, and risks of geoengineering technologies. Moreover, far more inclusive, transparent, and legitimate governance structures are also necessary. Here, too, the relevance of CBD X/33 becomes apparent, in which the current lack and possible need for such a science-based, transparent and effective structure is emphasised.

5.3 Conclusion

The SDGs and climate targets, while politically useful, are not a good mechanism on which to base decision on these technologies. They describe politically agreed-upon aims that are crucially important to steer on for political decision-making around climate policy and sustainable development, but they do not provide the right kind of proxy for decision-making on either CDR or SRM. Most fundamentally, these targets reduce incredibly complex systems to simple metrics. Only when the risks and impacts of these technologies are sufficiently clarified could the SDGs potentially come into play as mechanism for steering policy on geoengineering technologies. Taking SRM as an example, these metrics do not work neatly in the case of geoengineering. SRM potentially makes it possible reach the 1.5°C target in many different ways, with many different climatic configurations. Many of these climates might be worse than not using SRM at all, though some might conceivably limited damages. In all, these choices will have a range of different consequences. As such, the relationship between geoengineering technologies and politically agreed-upon targets that were agreed-upon for other reasons than assessing geoengineering technologies should be treated with extreme caution.

6 Conclusion

Since 2011, when the German Environment Agency published its last comprehensive assessment of geoengineering, parts of what was then called geoengineering have become an embedded assumption of climate politics. Partially, this has to do with justifiably escalating fears about climate change. At the same time, the story of the rapid normalisation and adoption of CDR in climate policy should also be reason for caution and perhaps even concern. Rather than an inclusive and transparent process in which all the pros and cons of CDR were weighed against those of mitigation, a complex dynamic in the science-policy interface rendered CDR a normal part of climate policy – and hence, for the purposes of policy, no longer 'geoengineering'. This normalisation of CDR was a feature of a particular political regime, in which the science policy interface works to maintain the suggestion it can solve anthropogenic climate change through 'win-win' approaches that allow for economic development while safeguarding the environment at the same time. Importantly, this normalisation – which is also looming for SRM – is not a deliberate process, but rather the consequence of the ways in which geoengineering are defined, weighed, assessed, and discussed in the science-policy interface. As a result, without enough critical scrutiny of its political desirability (or even practical feasibility), CDR technologies have become a key pillar of climate targets.

At the same time, CDR continues to be plagued by many debilitating issues, in terms of scale, cost, efficacy, and justice concerns. These issues were not magicked away by simply counting on CDR. Firstly, it remains unclear whether CDR can reasonably be expected to succeed at the scales now assumed in both IAMs and climate politics at large. Secondly, the tradeoffs to achieve such scales might be considerable, including justice concerns around land-grabbing and food security as well as bioecological concerns about biodiversity and hydrological cycles. Moreover, both these first two concerns are compounded by a third complication, that of possible political resistance against CDR measures from those affected by its implementation. As such, careful, critical, and society-oriented development of these technologies is necessary and desirable. Public opinion about different forms of technology should be taken seriously, as it will affect their potential for scale-up. Fourthly, there are important considerations of speed in terms of scaling up. According to climate scenarios, CDR should be scaled up and implemented as soon as it is possible. At the moment, we do not see those speeds materialize. Additionally, to do so in robust and fair ways seems difficult. SRM raises similar, but far more intractable questions. Ranging from concerns about who controls this highly invasive technology – and potential geopolitical conflict around this control – to fears about mitigation deterrence and the wielding of these technologies for political gain, sociopolitical and economic questions about the desirability and feasibility of these technologies abound. Technically, climatically, as we have seen, SRM also remains highly uncertain, an uncertainty that likely cannot ever fully be solved.

The intersection between climate targets, the SDGs, and geoengineering is caught within this uncertainty. Hypothetically, in an ideal world, geoengineering technologies could provide worthwhile complementary approaches to anthropogenic climate change. However, to paraphrase Clive Hamilton, in such a world, ironically, climate change would never have escalated to current proportions. In the world as it is, both CDR and SRM would have real risks and drawbacks. SRM, in particular, remains deeply uncertain. In a path forward that is guided, inter alia, by the principles of caution and rigour put forth in CBD X/33, these drawbacks should be taken seriously and be at the centre of deliberations about these technologies. And such considerations should be aware of implicit processes, recognising that knowledge and evaluations have political implications, that they condition the political world prior to political discussions.The case of CDR is a cautionary tale for SRM, a far more invasive and potentially catastrophic range of proposals. Already, SRM becomes part of the IPCC pathways that are renwed in the fast track. While this may potentially lead to a careful, nuanced assessment of SRM, it is also risky. A process of implicit normalisation similar to CDR should be avoided at all costs.

[FIN]

7 Bibliography

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A Annex: Overview of outcomes within the project *ReFoPlan 2021, Geoengineering: Mögliche Synergien und Effekte mit den Sustainable Development Goals*

A.1 Governance Workshop on Solar Radiation Modification (SRM)

February 13th – 14th, 2023, online. This workshop brought policymakers, civil society actors, practitioners, politicians, and scientists into conversation around the potential governance challenges of SRM, discussing questions such as:

- Can SRM fit into an effective, equitable, and sustainable climate governance framework?
- What are the physical and political risks associated with research and deployment?
- Is there a risk of mitigation deterrence related SRM research?

More information on the event, including the workshop report, can be found here.

A.2 Networking event on Solar Geoengineering

Feb 15th-16th, 2024, Dessau-Roßlau. Information on the event can be found here.

A.3 Discussion Paper on Solar Radiation Modification

The discussion paper has been informed by two technical expert discussions, held online on 15 September and 19 October 2022, on SAI and other methods of Solar Radiation Modification: Oomen, J., & Niesen, M. (2024). *Solar Radiation Modification (SRM): Intractable Governance and Uncertain Science*. German Environment Agency. https://www.umweltbundesamt.de/en/publikationen/solar-radiation-modification-srm-intractable

A.4 Geoengineering Research & Funding Landscape

Two factsheets (to be published on the German Environment Agency website) on major trends and developments in the funding landscape for SRM and CDR funding, respectively. An excel sheet detailing research projects on SRM > 100,000.00 EUR between 2007 and 09/2024, including details on funding, research discipline, the SRM technology in focus, and more.

A.5 Infographics on SRM

A poster on **Risks of Solar Radiation Modification** as well as **several illustrations of SRM technologies**:

- https://www.umweltbundesamt.de/publikationen/poster-risks-of-solar-radiation-modification-srm
- https://www.umweltbundesamt.de/en/topics/climate-energy/geoengineering - srm

B Annex: Terrestrial Carbon Dioxide Removal – Discussion Paper

B.1 Zusammenfassung

Carbon Dioxide Removal (auch negative Emissionstechnologien und CO2-Entnahme, CDR) bezeichnet eine Reihe von Maßnahmen und Technologievorschlägen, die dem anthropogenen Klimawandel entgegenwirken sollen, indem Kohlendioxid aus der Atmosphäre entfernt wird. Durch die Entnahme von Kohlendioxid in großem Maßstab könnte dessen Gesamtkonzentration in der Atmosphäre gesenkt werden, was zu einer geringeren globalen Erwärmung führen würde. In der Regel werden diese Technologien als Ergänzung zu konventionellen Emissionsminderungsmaßnahmen betrachtet. Häufig werden CDR-Technologien in drei Bereiche unterteilt: natürliche oder terrestrische, technische und marine CDR. Zu den terrestrischen und technischen CDR-Methoden gehören Bioenergie mit anschließender Abscheidung und geologischer Speicherung des CO_2 (BECCS), direkte Abscheidung von CO_2 aus der Atmosphäre (DAC), Pflanzenkohle, modifizierte bzw. beschleunigte Verwitterung von Gestein und - nach einigen Klassifizierungen - Aufforstung und Wiederaufforstung. Zu den marinen CDR-Methoden (mCDR) hingegen gehören die Wiederherstellung von (Küsten-)Feuchtgebieten (blauer Kohlenstoff), die Erhöhung der Alkalinität, der künstliche Ozeanauftrieb sowie die Eisendüngung. Diese Klassifizierung bleibt unvollständig, ebenso sind weitere Unterteilungen von CDR denkbar. Zahlreiche der vorgeschlagenen Technologien binden Kohlenstoff durch biologische oder industrielle Prozesse an Land und speichern diesen anschließend im oder unter dem Meer, oder umgekehrt. In diesem Diskussionspapier behandeln wir tCDR als eine Reihe von technologischen Ansätzen auf Basis eines Dialogs mit Expert*innen am 26. Oktober 2022.

Seit dem Klimaabkommen von Paris im Jahr 2015 ist die Entnahme von Kohlendioxid zu einem festen Bestandteil der Klimapolitik geworden. Es setzt sich die Ansicht durch, dass CDR-Technologien erforderlich sind, um die 1,5°C- und sogar die 2°C-Ziele zu erreichen, auch wenn es ernsthafte Meinungsverschiedenheiten und Zweifel darüber gibt, inwieweit CDR praktisch umsetzbar oder sozial und politisch wünschenswert ist (IPCC, 2022). Zu einem gewissen Grad stellen CDR-Technologien gar ein wichtiges Mittel dar, mit dem Wissenschaftler*innen und politische Entscheidungsträger*innen die Machbarkeit dieser Klimaziele aufrechterhalten (van Beek et al., 2022). Die meisten klimapolitischen Modellprojektionen sehen eine starke Nutzung von CDR in den kommenden Jahrzehnten vor, obwohl es weit verbreitete Kritik an den zugrunde liegenden Annahmen gibt, die CDR-Technologien in den Modellen attraktiv und vielversprechend erscheinen lassen (z. B. Beck & Oomen, 2021; Carton et al., 2020). Einem Konsensbericht der U.S.-amerikanischen National Academy of Sciences aus dem Jahr 2019 zufolge könnte die sichere und effiziente weltweite Anwendung bestehender CDR-Methoden bis 2050 bis zu 10 Gigatonnen (Gt) CO2 pro Jahr und bis 2100 eventuell sogar bis zu 20 Gt binden (NAS, 2019), obwohl diese Zahlen umstritten und ungesichert sind.

Die Grundannahme von CDR ist, dass anthropogene Aktivitäten CO2 aus der Atmosphäre entfernen und es dauerhaft in geologischen, terrestrischen oder ozeanischen Reservoiren speichern können. Potenziell könnte CO2 sogar in Produkten durch Kohlenstoffabscheidung und -nutzung (CCUS) gespeichert werden, obwohl der Gesamtgewinn begrenzt wäre. Alle IPCC-Pfade stützen sich auf CDR, um zumindest die so genannten restlichen oder schwer zu vermeidenden Emissionen auszugleichen. Die meisten Pfade stützen sich auch auf den Ausgleich von

Überschreitungen des Kohlenstoffbudgets. Mit 2023 als Basisjahr wird das verbleibende Kohlenstoffbudget, um unter 1,5°C Erwärmung zu verbleiben (bei einer Wahrscheinlichkeit von 50%), auf etwa 250 Gigatonnen (Gt) CO2-Emissionen geschätzt (50% Wahrscheinlichkeit, Forster et al., 2023). Bei der derzeitigen Rate der CO2-äquivalenten Emissionen von etwa 57,4 GtC02e pro Jahr (UNEP, 2023) könnte das verbleibende Kohlenstoffbudget demnach schnell erschöpft sein.

CDR ist als umfassendere Kategorie umstritten und unsicher. Es bestehen nach wie vor erhebliche Fragen zum Gesamtpotenzial von CDR-Technologien (European Academies Science Advisory Council, 2018; IPCC, 2022b; Luderer et al., 2021). Ebenso könnten die wirtschaftlichen Kosten von CDR erhebliche Hürden darstellen (Fuss et al., 2018). Neben Fragen zu Kosten und Potenzialen birgt tCDR auch erhebliche politische und soziale Risiken, darunter das Risiko der Ablenkung von Maßnahmen zur Emissionsminderung (Beck & Mahony, 2018; Beck & Oomen, 2021), Landgrabbing und Gerechtigkeitsbedenken (Honegger et al., 2018). Darüber hinaus können tCDR-Methoden auch positive und negative Auswirkungen auf verschiedene Ökosysteme haben (IPCC, 2022b, 2022a). Die genauen Auswirkungen von CDR-Technologien sind jedoch sehr kontextspezifisch. Sie hängen von den spezifischen Technologien, der Art der Umsetzung und dem Umfang des Einsatzes ab.

In einem Online-Gespräch mit Expert*innen, das vom Deutschen Umweltbundesamt am 26. Oktober 2022 durchgeführt wurde, wiesen die Expert*innen auf die Notwendigkeit klarer und robuster Governance- und Bewertungsverfahren für tCDR hin. Dies steht im Zusammenhang mit der allgemein anerkannten Notwendigkeit einer strengen und kritischen Untersuchung der Risiken und des Potenzials von tCDR. Die wichtigsten Erfordernisse für die Bewertung und Steuerung sind die folgenden:

- Die Annahmen, die den Projektionen und Bewertungen der CDR-Potenziale und der Klimapolitik zugrunde liegen, müssen sehr sorgfältig geprüft werden. So würden beispielsweise Annahmen über die Menge der aus der Landwirtschaft freigesetzten Flächen das Potenzial der landgestützten CDR stark beeinflussen. Auch die Annahmen über die verstärkte Verwitterung von Steinen betreffen den Prozentsatz der landwirtschaftlichen Flächen, auf denen Mineralien ausgebracht werden könnten, die Gestaltung der Bergbauinfrastruktur sowie Sättigungseffekte. Annahmen über Energiekosten spielen eine weitere entscheidende Rolle bei tCDR-Projektionen, da sie die wirtschaftliche Machbarkeit und Skalierbarkeit energieintensiver Technologien beeinflussen. Eine Über- oder Unterschätzung dieser Kosten kann das wahrgenommene Potenzial verschiedener CDR-Methoden, wie DAC oder BECCS, erheblich verändern.
- Die ökologischen Folgen, die soziale Machbarkeit, die Akzeptanz und die Gerechtigkeit der tCDR-Methoden müssen in die Bewertungsverfahren und in die politischen Prognosen einbezogen werden. Solche Überlegungen wirken sich unweigerlich auf den Umfang und das Ausmaß des tCDR-Potenzials aus.
- Klare Definitionen und Verfahren für die Anrechnung von Klimschutzmaßnahmen im Zusammenhang mit CDR sind notwendig. Mehrere Sachverständige sprachen sich für ein Anrechnungssystem aus, das CDR von Klimaschutzmaßnahmen trennt, um sicherzustellen, dass die Anrechnung von CDR nicht dazu führt, dass auch Emissionen kompensiert werden, nicht zu den sog. Residual- oder schwer zu reduzierenden Emissionen zählen.

- Auch Governance-Risiken müssen berücksichtigt werden. Neben Fragen der Ablenkung von der Emissionsminderung und der Zuständigkeit (diffus oder zentral organisiert, direktiv oder marktorientiert) geht es dabei auch um die Zukunftssicherheit der Governance-Verfahren und die Frage der künftigen Stabilität und Governance sowohl der Kohlenstoffabscheidung als auch der Kohlenstoffsenken.

B.2 Summary

Carbon Dioxide Removal (also referred to as negative emissions technologies and greenhouse gas removal, CDR) describes a range of measures and technology proposals designed to counteract anthropogenic climate change by removing carbon dioxide from the atmosphere. By removing carbon dioxide on a large scale, its overall concentration in the atmosphere could be lowered, resulting in less global warming. Typically, these technologies are considered complementary to conventional emission reduction measures. Often, CDR technologies are divided into three areas (natural or terrestrial, engineered, and marine CDR). Terrestrial and engineered CDR (tCDR) methods include bioenergy with carbon capture and storage (BECCS), direct air capture (DAC), biochar, modified weathering or enhanced weathering, and, by some classifications, afforestation and reforestation. Marine CDR (mCDR) methods, on the other hand, include (coastal) wetland restoration (blue carbon), alkalinization, artificial upwelling, and ocean iron fertilization. It is important to note that these classifications are imperfect and other subdivisions are conceivable. Many proposed technologies capture carbon via biological or industrial processes on land and store them in or under the sea, and vice versa. In this discussion paper, we address tCDR as a range of proposed technologies, based on an expert workshop held on 26 October, 2022.

Since the 2015 Paris Agreement, carbon dioxide removal has become an integral part of climate policy. There is an emerging view that CDR technologies are needed to achieve the 1.5°C and even 2°C targets, although there are serious disagreements and doubts about the extent to which CDR is practically feasible or socially and politically desirable (IPCC, 2022). To some extent, CDR technologies are even an important means by which scientists and policymakers maintain the feasibility of these climate targets (van Beek et al., 2022). Most climate policy model projections foresee heavy use of CDR in the coming decades, although there is widespread criticism of those underlying assumptions that make CDR technologies appear attractive and promising in models (e.g., Beck & Oomen, 2021; Carton et al., 2020). According to a 2019 consensus report from the National Academy of Sciences, safe and efficient worldwide application of existing CDR methods could sequester up to 10 gigatons (Gt) of CO_2 per year by 2050, and perhaps as much as 20 Gt by 2100 (NAS, 2019), although these numbers are disputed and uncertain.

As a broader category, CDR is controversial and uncertain. Significant questions remain about the overall potential of CDR technologies (European Academies Science Advisory Council, 2018; IPCC, 2022b; Luderer et al., 2021). Similarly, their economic costs of CDR could be prohibitive (Fuss et al., 2018). In addition to questions about cost and potential, tCDR also poses major political and social risks. the risk of mitigation deterrence (Beck & Mahony, 2018; Beck & Oomen, 2021), land grabbing, and equity concerns (Honegger et al., 2018). In addition, land-based CDR methods may also have positive and negative impacts on the environment, ecology, and hydrology (IPCC, 2022b, 2022a). The exact impacts of CDR technologies are, however, highly context-specific. They depend on the specific technologies, the type of implementation, and the scale.

In an online conversation with experts convened by the German Environment Agency on 26 October, 2022, experts signalled a need for clear and robust governance and assessment procedures for tCDR. This ties into a wider recognition of a need for both rigorous and critical investigation of the risks and potential of tCDR. Key necessities for assessment and governance signalled the following:

- The assumptions underlying the projections and assessments of CDR potentials and climate policy need to be considered very carefully. For example, assumptions about the amount of released land from agriculture will deeply affect the potential of land-based CDR. Likewise, assumptions about enhanced weathering center around the percentage of agricultural land that minerals could be applied to, the provision of the mining infrastructure, as well as saturation effects. Assumptions about energy costs play another critical role in CDR projections, as they influence the economic feasibility and scalability of energy-intensive technologies. Over- or underestimating these costs can significantly alter the perceived potential of various CDR methods, such as DAC or BECCS.
- Ecological consequences, social feasibility, acceptance, and justice of tCDR methods will need to be incorporated in assessment procedures and in policy projections. Such considerations will inevitably affect the scope and scale of tCDR potential.
- Clear definitions and governance procedures around accounting for mitigation in relation to CDR are necessary. Several experts argued for an accounting system that separates CDR from mitigation, to ensure that carbon accounting does not allow CDR to compensate for relatively easily abated emissions.
- Governance risks also need to be considered. Beyond questions of mitigation deterrence, questions of responsibility (diffuse or centrally organised, directive or market-based), such questions include future-proofing governance procedures, addressing questions around the future stability and governance of both carbon capture and carbon sinks.

B.3 Introduction

Expert talks held on 26 October, 2022, convened by the German Environment Agency (Umweltbundesamt, UBA) in collaboration with the Copernicus Institute of Sustainable Development of the University of Utrecht addressed the scientific and technical feasibility of terrestrial carbon dioxide removal (tCDR). Since the 2015 Paris Agreement, carbon dioxide removal (CDR) has become an integral part of climate policy. There is an emerging view that CDR technologies are needed to achieve the 1.5°C and even 2°C targets. However, there are serious disagreements and doubts about the extent to which CDR is practically feasible or socially and politically desirable (IPCC, 2022). Most climate policy model projections foresee heavy use of CDR in the coming decades, although criticisms abound regarding the assumptions underlying these models, which often present CDR technologies as overly promising (Beck & Mahony, 2018; Beck & Oomen, 2021; Carton et al., 2020; van Beek et al., 2022). Carbon Dioxide Removal (also referred to as negative emissions technologies and greenhouse gas removal) describes a range of measures and technology proposals designed to counteract anthropogenic climate change by removing carbon dioxide from the atmosphere. By removing carbon dioxide on a large scale, its overall concentration in the atmosphere could be lowered, resulting in less global warming. As such, CDR is typically considered as complementary to conventional emission reduction measures. According to a 2019 research agenda of the U.S. National Academy of Sciences, safe and efficient application of existing CDR methods could sequester up to 10 gigatons (Gt) of CO2 annually by 2050, and perhaps as much as 20 Gt by 2100 (National Academies of Sciences, 2019).

CDR comprises a great variety of proposed interventions in the planetary environment. The methods to capture carbon dioxide range from (re)planting forests to enhancing the absorptive capacity of oceans to geochemical and industrial processes. Likewise, storing the captured carbon would happen in a variety of ways, such as in ecosystems (such as forest), geological formations on land or under the sea, or (to a limited extent) in the built environment. As such, CDR defies neat classification. Often, CDR technologies are divided into three areas (natural or terrestrial, engineered, and marine CDR). Terrestrial and engineered CDR methods include bioenergy with carbon capture and storage (BECCS), direct air capture (DAC), biochar, modified weathering or enhanced weathering, and, by some classifications, afforestation and reforestation. Marine CDR methods, on the other hand, include (coastal) wetland restoration (blue carbon), alkalinization, artificial upwelling, and ocean iron fertilization. It is important to note that these classifications are imperfect and other subdivisions are conceivable. Many proposed technologies capture carbon via biological or industrial processes on land and store them in or under the sea, and vice versa. Despite the imperfection of such classification, however, this discussion paper adheres to this classification. In this paper we address terrestrial and engineered methods of carbon removal, based on the discussions held on the 26th of October. In a separate discussion paper, we address marine CDR (henceforth mCDR), based on a similar workshop held on 1 December 2022. It is important to note from the outset, however, that scientific classifications of such technologies have political consequences, as they co-determine the types of governance systems set up around technological concepts. As such, the division between these classifications does not always hold up. It also means that classifying CDR methods is a question for governance as much as science, as it influences both political and policy proposals around governing and developing such technologies.

The basic assumption of CDR is that anthropogenic activities can remove CO_2 from the atmosphere and permanently store it in geologic, terrestrial, or oceanic reservoirs. Potentially, CO_2 could even be stored in products through carbon capture and utilization (CCUS), although the overall gain would be limited. All IPCC pathways rely on CDR to offset at least so-called residual or hard-to-avoid emissions. Most also rely on carbon budget overshoot offsets. With 2023 as a base year, the remaining carbon budget to stay below 1.5°C (50% likelihood) is estimated at about 250 gigatons (Gt) of CO_2 emissions while for the 2°C target, the remaining budget would be about 1150 Gt (50% likelihood, Forster et al., 2023). At the current rate of CO2-equivalent emissions of about 57.4 GtC02e per year (United Nations Environment Programme, 2023), the remaining carbon budget for the 1.5°C target in particular might be exhausted rapidly. To meet the climate targets, the models assume substantial use of CDR. As the 6th IPCC report states:

> *'In modelled pathways that report CDR and that limit warming to 1.5°C (>50%) with no or limited overshoot, global cumulative CDR during 2020-2100 from bioenergy with carbon dioxide capture and storage (BECCS) and direct air carbon dioxide capture and storage (DACCS) is 30-780 GtCO2 and 0-310 GtCO2, respectively. In these modeled pathways, the AFOLU sector contributes 20-400 GtCO2 net negative emissions. Total cumulative net negative CO2 emissions including CDR deployment across all options represented in these modelled pathways are 20-660 GtCO2. In modelled pathways that limit warming to 2°C (>67%), global cumulative CDR during 2020-2100 from BECCS and DACCS is 170-650 GtCO2 and 0-250 GtCO2 respectively, the AFOLU sector contributes 10-250 GtCO2 net negative emissions, and total cumulative net negative CO2 emissions are around 40 [0-290] GtCO2. (high confidence)' (IPCC, 2022b, SPM WGIII: p. 29).*

At the same time, the modelled pathways utilize the portfolio of CDR measures in various ways, for example regarding the reliance on BECCS: some pathways that assume a low energy demand and/or a rapid transition to sustainable diets and thus a change in land use towards afforestation forgo the use of BECCS completely or for the most part (IPCC, 2018; van Vuuren et al., 2018).

Overall, CDR is still fraught with controversy and uncertainty. Significant questions remain about the potential of CDR technologies (European Academies Science Advisory Council, 2018; IPCC, 2022b; Luderer et al., 2021), as well as the potential of tCDR in particular (National Academies of Sciences, 2019). Similarly, the economic costs of CDR could be prohibitive (Fuss et al., 2018). The economic viability of CDR is thus heaviliy reliant on carbon pricing, and the form of such pricing, amongst other factors, will influence which CDR methods become economically feasible on a large scale. For many of these technologies, it is unclear how great the potential for expansion is. The IPCC report also acknowledges these uncertainties:

'CDR methods vary in terms of their maturity, removal process, time scale of carbon storage, storage medium, mitigation potential, cost, co-benefits, impacts and risks, and governance requirements (high confidence). Specifically, maturity ranges from lower maturity (e.g., ocean alkalinization) to higher maturity (e.g., reforestation); removal and storage potential ranges from lower potential (3 GtCO2 yr-1, e.g., agroforestry); costs range from lower cost (e.g., USD-45-100 per tCO2 for soil carbon sequestration) to higher cost (e.g., USD100-300 per tCO2 for DACCS) (medium confidence).' (IPCC, 2022b, SPM WGIII: p. 40).

In addition to questions about cost and potential, terrestrial CDR also poses major political and social risks. Many observers have expressed concerns: the risk of mitigation deterrence (Beck & Mahony, 2018; Beck & Oomen, 2021), land grabbing, and equity concerns (Honegger et al., 2018). In addition, land-based CDR methods may also have positive and negative impacts on the environment, ecology, and hydrology (IPCC, 2022b, 2022a). The exact impacts of CDR technologies are, however, highly context-specific. They depend on the specific technologies, the type of implementation, and the scale.

B.4 CDR and 'Geoengineering'

Until recently, CDR often used to be described as 'geoengineering'. Geoengineering, as a term, historically connoted a wide range of large-scale interventions in the planetary environment. Originally, the term included CDR measures as well as solar radiation techniques. It has enjoyed a wide usage both in relation to anthropogenic climate change (e.g. National Academies of Sciences, 2021; National Academy of the Sciences, 1992; Royal Society, 2009; Umweltbundesamt, 2011) and lithosphere geoengineering (e.g. Civil Engineering Research Foundation [CERF], 1994; Morgenstern, 2000; National Research Council (U.S.), 2006), as well as occasionally in ecology, in relation to treating hypoxic dead zones in seas and lakes (Lürling et al., 2016; Stigebrandt et al., 2015). Although these interventions share a family resemblance in terms of the underlying rationality and aims (Oomen & Meiske, 2021), in the public eye geoengineering has increasingly come to be synonymous with 'climate (geo)engineering'. In relation to climate change, the term geoengineering first appeared alongside an early CDR proposal, which suggested storing CO_2 in thermohaline currents (Marchetti, 1977). Since the mid-2000s, the term 'geoengineering' has increasingly come to be used to along the lines of the Royal Society's 2009 definition of the term: 'deliberate large-scale intervention in the Earth's climate system, in order to moderate global warming' (Royal Society, 2009: ix). The term geoengineering is an umbrella term, connoting a wide range of diverging technologies and interventions. It includes both carbon dioxide removal (CDR), technologies aimed at addressing the root cause of climate change by capturing and storing greenhouse gases in myriad ways, and solar radiation modification (SRM), technologies aimed at masking warming and limiting the direct damage of climate change. This discussion paper is the third in a series of three discussion papers on the issue of 'geoengineering'. They are the precursor to a renewed positioning by the UBA on geoengineering. Since 2009, a series of scientific assessments of geoengineering have been published. In 2009, the Royal Society published the first major report on 'geoengineering', which at the time included both carbon dioxide removal (CDR) methods and SRM. In 2015, the National Academy of Sciences published two reports on the same topic, using the term 'climate intervention. Responding to an increasing demand to treat CDR and SRM separately, the NRC had separate reports for both technological categories (National Research Council, 2015a, 2015b). In 2019, 2021, and 2022, the NAS published three more reports on research strategies for tCDR, SRM, and mCDR (National Academies of Sciences, 2019; 2021, 2022).

In 2011, the UBA published a report on geoengineering, as a broad technological category. Since 2011, much has changed in the political and scientific debate around climate change and geoengineering – although many of the same uncertainties remain. For one, CDR and SRM have become increasingly differentiated, increasingly treated in isolation from one another. As a result, the term 'geoengineering' has also become less common, especially in relation to CDR. In this discussion paper series, we recognise this differentiation, acknowledging both the inevitable imperfection and necessity of classifying geoengineering. This second discussion paper addresses land-based (terrestrial) CDR (tCDR) and direct air capture (DAC). The third in the series will zoom in on marine forms of carbon dioxide removal (mCDR). A previous first paper addressed SRM as a technological category.

A final note on terminology. In the past, CDR technologies were also known through accounting terms such as "negative emissions technologies" (NETs) because they are intended to counteract what are known as "positive emissions." In addition to CO_2 capture, approaches to capture other greenhouse gases, such as methane, also exist. As a result, both scientists and assessments have also used greenhouse gas removal (GGR) as an umbrella term. In its most recent reports, the IPCC has consistently used the term carbon dioxide removal. As such, this discussion paper will adhere to this usage.

Insights from expert talks

As our expert talks made clear, the need for sizeable CDR implementation is almost universally accepted by climate scientists. However, most worry that CDR leads to **mitigation deterrence**, as it may delay mitigation commitments in the present or lead to high amounts of residual emissions in the future. Moreover, all experts raised questions of governance, monitoring, social feasibility, and acceptance. With reference to past protests in Germany against the use of CCS, for example, it was also pointed out that by neglecting social acceptance, model-based projections could overestimate the potential of CCS even beyond the uncertainties of its permanence.

In contrast to mitigation measures, CDR measures are immature, have unclear potentials, costs and side effects, unclear controllability. As such, CDR could never take the place of strict mitigation commitments. All experts present in the workshop also favored clear and robust ways to account for the amounts of CDR necessary. Particularly present was the worry that CDR would not be used to offset hard to abate emissions but for emissions that should have been mitigated. Moreover, several experts highlighted a tendency to overestimate the costs of mitigation while underestimating the economic and social benefits of a successful energy transition, as well as underestimating the true costs of CDR.

B.5 Terrestrial Carbon Dioxide Removal: The Technologies

Terrestrial carbon dioxide removal encompasses a wide range of technologies. Some proposals, such as afforestation and reforestation, aim to use, alter, or restore existing ecosystems to enhance their capacity to capture and store carbon. Other proposals, such as enhanced weathering, suggest to use and accelerate geological processes, storing carbon in weathered material on the seabed. Yet other technologies are wholly technical and industrial, in that they propose to set up an industrial system to capture carbon dioxide from ambient air. Below, we briefly address a number of prominent technologies, outlining their basic premise, their proposed manner of both capture and storge, as well as their possible potential and major risks. The selection of technologies discussed here is intentionally focused and not exhaustive. Other analyses include a broader range of methods, including biochar or agroforestry, reflecting the dynamic and evolving nature of CDR research. Current initiatives like the BMBF-funded CDRterra project are exploring a comprehensive array of methods and their combinations. A comprehensive factsheet of land-based CDR has been published by CDRterra (in German). Whereas this report refrains from examining the storage side of the technologies in this brief overview (in particular BECCS/DACCS), CDRterra takes these into account. Here, we also refer to the position paper on CCS recently published by the German Environment Agency. For an assessment of CDR options for Germany, Borchers et al. (2024) offer a comprehensive overview. Beyond the German context, we also refer the reader to the 2015 and 2019 National Academies reports on CDR as well as the IPCC's 2022 6th Assessment report and its 2018 report on the 1.5°C goal (IPCC, 2018, 2022b).

B.5.1 Direct Air Capture (DAC)

The technologies gathered under the term DAC are concerned with the capture of ambient $C0_2$ using technological devices. This is achieved by saturating liquid or solid capture material, from which the $C0_2$ is subsequently released and stored over the long term (National Academies of Sciences, 2019; Luderer & Sörgel 2021). The global mitigation potential per year has been estimated at 5-40 Gt CO_2 (Babiker et al., 2022). These processes require a large amount of energy, which results from the low air concentration of $C0_2$, which directly impacts the capture efficiency of the technology. Thus, when using fossil energy sources, high associated costs ensue (National Academies of Sciences, 2019; National Research Council, 2015a). The use of renewables, on the other hand, could lead to competition with other sectors (Smith et al., 2023). Environmental risks potentially arise from the increased water use of some DACCS concepts (Smith et al., 2023). Although potentially advantageous in terms of permanence, challenges arise from the possible scarcity of adequate geological storage options, which could lead to competition with other technology approaches that use CCS. Only combined with permanent storage, DACCS can contribute to negative emissions.

B.5.2 Bio-energy carbon capture and storage (BECCS)

As a category, BECCS includes those technologies that capture CO_2 from biomass energy production in order to store it permanently. Simply put, BECCS suggests using biomass as an energy source and capture the emissions of this energy at the source. In such a process, the biomass used for energy production would capture carbon dioxide from ambient air as it is growing. This carbon can subsequently be captured and store when the biomass is used as an energy source. Like DACCS, BECCS generally imagines storing carbon in geological formations. Different processes can yield different energy carriers, including biogas, bioliquids, and biogenic hydrogen in addition to electricity, and differ greatly in their C02 capture potential. The substitution potential for fossil fuels, on the other hand, represents an additional potential benefit. The approaches are united by the risk of land-use competition with biodiverse natural areas, as well as food production, with numerous potential consequences ranging from unwanted CO2 emissions to impacts on soil and water, and health risks.

B.5.3 Afforestation & Reforestation

Afforestation and reforestation aim to take advantage of the natural ability of trees to sequester and store carbon on a large scale. Afforestation would often convert agricultural land into forests. Reforestation would involve replanting trees in previously deforested areas. The contribution of forest sinks depends critically on regional factors such as climate and humidity, soil type, tree species, and especially forest management, which must be continuously maintained to preserve storage and is susceptible to disturbance, not least by climate change-induced more frequent events such as droughts, pest infestations, and forest fires. Limiting factors for afforestation for countries such as Germany lie in limited unused areas (Mengis et al., 2022). Estimates of the annual potential by 2050 are 0.5-3.6 Gt CO_2 (Fuss et al., 2018). (Re-) afforestation without a near-natural orientation poses risks to biodiversity similar to BECCS.

B.5.4 Enhanced Weathering

This process is based on the natural weathering process of rock decomposition, in which CO_2 acts as an input. Artificial acceleration of this process, which is particularly promising for basaltic rocks, will therefore capture significantly more CO2 per time period. There is yet limited evidence on the mitigation potential of Enhanced Weathering, although Fuss et al. give an estimate of 2-4 GT CO_2 per year (Fuss et al., 2018). One approach to acceleration is to increase the surface area, for example by processing it into rock flour and applying it to arable land or seawater. Side effects therefore lie in influencing the pH value of water and soil (positive effects are also possible here, such as improved plant growth), the release of heavy metals and thus damage to health, ecological effects of rock mining and its transport, as well as dust generation with its effect on air quality (Babiker et al., 2022), as well as large amounts of energy required from mining and processing the rocks to the necessary infrastructure to transport them to the application sites. There are thus still numerous gaps in knowledge about the energetic efficiency and possible adverse effects and possible co-benefits.

Insights from expert talks

In the expert workshops, it emerged that all proposed CDR methods carry significant uncertainties. The potential for all CDR methods is limited not only by technical or bioecological constraints but also by political, economic and social considerations. The sustainable implementation of CDR is complex and not without risks. For example, large-scale cultivation of biomass for energy use, storage, or biochar production would require extensive irrigation, which, if not managed sustainably, could lead to the risk of exceeding water use limits. Even afforestation and reforestation are not without risks, as monocultures of fast-growing but less climate-resilient species could threaten biodiversity and undermine long-term carbon sequestration

Most experts expressed worries and uncertainties about:

- **risk and monitoring** of carbon dioxide removal as well as leakages from carbon sinks

- The **permanence and long-term potential** of different technologies
- The impact of **climate change** on CDR-potentials, especially regarding natural sinks such as forests
- The need for clarity regarding **goals and carbon accounting:** how should CDR be accounted and should it be connected to conventional mitigation?
- **Land use competition**: Many CDR technologies, such as afforestation and BECCS require large areas of land
- For CDR to be successful (in Germany),hard-to-abate emissions need to be reduced further, e.g., by peatland restoration

B.6 What we (don't) know about tCDR

The expert workshop made clear that tCDR is a necessary domain of research and development fraught with complications. It is not at all clear what the potentials of different technologies are, nor how they interact with one another. The estimates for many technologies vary by an order of magnitude or more, even when accounting only for geophysical, bioecological, and technical constraints. When economic considerations and social, political, and justice issues enter the equation such uncertainties compound further. In any case, it is unlikely that tCDR technologies will reach the optimistic potentials as they appear in assessment reports. Even more uncertain is whether they will reach the potential that is assumed in many climate-emissions projections based on integrated assessment modelling (IAM) and corresponding national climate policies. As a recent investigation by Lisette van Beek and colleagues (van Beek et al, 2022) found, many IAM modellers themselves are deeply sceptical about the potential of real-world climate policy to achieve the CDR potentials their models assume.

The expert discussion suggested that even under optimistic assumptions, land-based tCDR potential in Germany is not expected to be sufficient to offset the calculated residual emissions from 2045. Compensating for residual emissions using land-based and nature-based tCDR would only be possible in two ways. Firstly, by further reducing residual emission, especially in agriculture, through land use change, such as the rewetting of peatlands. Secondly, the available area for land-based CDR methods must be increased by decreasing agricultural demands on lands, which means the need for significant dietary changes. Even if successful, however, it is likely that other forms of CDR will be needed as a supplement to 'nature-based solutions' to be able to compensate for residual emissions.Not least against this backdrop of potential political conflicts arising from land-use competition, any undertaking to determine the potential and role of tCDR in climate policy needs to clearly communicate its basic assumptions. Numerous calculations of the potential of land-based methods, for instance, assume that CDR will serve to compensate for so-called hard-to-abate emissions. In other terms, CDR would come into play as soon as and insofar as emission reduction is considered too costly or infeasible after a certain point in time. This assumption, however, drew some criticism during the expert discussions: The specification of the socially acceptable remaining amount of emissions cannot be made objectively. The potential and use of CDR would thus become an object of political negotiation, which might lead to mitigation deterrence - such as in the form of delaying tactics, pointing to alternatives, or overestimating the costs of emissions avoidance. Moreover, setting a transitional time limit between a climate policy of emissions reduction and CDR might create a time trap in that any emissions remaining at a fixed point in time would default to CDR. Conversely, this limit could jeopardize the inclusion of CDR measures in earlier climate policy portfolios. Given the political risks attached to the narrative around CDR as a top-up mechanism for incomplete emissions reductions, the fundamental assumptions of CDR and their potential implications must be scrutinized.

B.7 Conclusion

Since 2011, when the German Environment Agency published its last comprehensive assessment of geoengineering, carbon dioxide removal (CDR) has evolved from a theoretical concept to an embedded component of climate policy. Over recent years, a complex interplay between science and politics has established CDR as necessary for achieving climate targets. This has rendered CDR as inevitable, despite ongoing concerns about its feasibility and risks (Carton et al., 2020; Stoddard et al., 2021; van Beek et al., 2020, 2022). As CDR has become more integrated into climate strategies, there has been a growing move away from classifying it under the broader term 'geoengineering.' As a result, ‚geoengineering' is increasingly associated with SRM, continues to be a source of significant controversy, while CDR is regarded as a distinct approach. Despite its growing acceptance, there remains substantial scientific uncertainty regarding the true potential of terrestrial CDR, with experts generally agreeing that its contributions, while important and promising, may not fully meet the expectations set by current models and projections.

From the expert discussions, it became clear that experts converge on several key issues. Firstly, careful, critical, and society-oriented development of these technologies is necessary and desirable. Secondly, tCDR should be scaled up and implemented once it is possible to do so in robust and fair ways. At the same time, the potential for such technologies should not be overestimated – overhyping these technologies is a real risk. Thirdly, public opinion about different forms of technology should be taken seriously, as it will affect their potential for scale-up. Many experts, however, are worried that the somewhat artificial distinction between ‘nature-based solutions’ and other forms of CDR holds considerable risks. The positive connotation of natural sinks invites greenwashing. Simultaneously, other technologies appear more ‘technological’ and invasive in comparison.

Finally, and most importantly, all CDR experts present in the workshop recognised the need for comprehensive and critical forms of CDR governance and assessment. Throughout the workshop, the key necessities for assessment and governance were the following:

- The **assumptions** underlying the projections and assessments of CDR potentials and climate policy need to be considered very carefully. For example, the **assumptions** made about the amount of released land from agriculture will deeply affect the **potential of land-based CDR**. Likewise, assumptions about enhanced weathering centre around the percentage of agricultural land that minerals could be applied to, the provision of the mining infrastructure, as well as **saturation effects**. Whether or not saturation effects are considered in models has critical implications for evaluating the potential of CDR technologies.
- Ecological consequences, social feasibility, acceptance, and justice of tCDR methods will need to be incorporated in assessment procedures and in policy projections. Such considerations will inevitably affect the scope and scale of tCDR potential.
- **Clear definitions and governance procedures** around accounting for mitigation in relation to CDR are necessary. Several experts argued for an accounting system that

separates CDR from mitigation, to ensure that carbon accounting does not allow CDR to compensate for relatively easily abated emissions.

- **Governance risks** also need to be considered. Beyond questions of mitigation deterrence, questions of responsibility (diffuse or centrally organised, directive or market-based), such questions include **future-proofing** governance procedures, addressing questions around the future stability and governance of both carbon capture and carbon sinks.

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B.9 Agenda

Experts: Prof. Dr. Julia Pongratz, Dr. Jessica Strefler, Prof. Dr. Jens Hartmann, Dr. Sabine Mathesius, Prof. Dr. Thomas Hickler, Prof. Dr. Eric Gawel, Prof. Dr. Silke Beck, Dr. Nils Matzner

Four session of 75 minutes on:

- Was ist tCDR? Technische Versprechen: Wissensstand, Entwicklung und Unsicherheiten
- Wirkungen von CDR in Klima- und Ökosystem(en)
- Geoengineering im Kontext: Kosten, Klimaschutz & Governance
- Implikationen für das UBA

B.9.1 9.30-10.45: Sitzung 1: Was ist tCDR?

Eröffnung durch Dr. Jeroen Oomen

Vorstellung der Expert*innen

Prof. Dr. Julia Pongratz: *Was ist (landbasierte) CDR? Was ist der aktuelle Forschungsstand zu Potenzial und Risiken der verschiedenen Technologien?*

Dr. Jessica Strefler: Interaktionen zwischen Emissionsvermeidung und CDR

B.9.2 11.15-12.30: Session 2- Wirkungen von CDR in Klima- und Ökosystem(en)

Prof. Dr. Jens Hartmann: *Was ist Enhanced Weathering und was sind seine maßgeblichen Potenziale und Risiken?*

Dr. Sabine Mathesius: *Welche Limitierungen der landbasierten CDR-Methoden ergeben sich durch planetare Grenzen und das Klimasystem?*

Prof. Dr. Thomas Hickler*: Zielkonflikte und Synergien mit Biodiversitätsschutz, Ökosystemleistungen und Klimaanpassung*

B.9.3 14.00-15.15: Sitzung 3 - Geoengineering im Kontext

Prof. Dr. Eric Gawel: *tCDR interdisziplinär: Was sind gesellschaftliche Nutzen und Kosten? Wie lassen sie sich aus ökonomischer, sozialer & juristischer Perspektive bewerten?*

Prof. Dr. Silke Beck, Dr. Nils Matzner: *Gesellschaftliche und politische Dimensionen von tCDR: Erkenntnisse aus dem BioNet-Projekt*

B.9.4 15.45-17.00: Sitzung 4 – Implikationen für das UBA

Diskussion über die Positionierung des UBA zu CDR

Welche Bedingungen ermöglichen eine nachhaltige Umsetzung von CDR?

Erkenntnisse des Tages & Schlusswort von Dr. Jeroen Oomen

C Annex: Marine Carbon Dioxide Removal – Discussion Paper

C.1 Zusammenfassung

Carbon Dioxide Removal (auch negative Emissionstechnologien und CO2-Entnahme, CDR) bezeichnet eine Reihe von Maßnahmen und Technologievorschlägen, die dem anthropogenen Klimawandel entgegenwirken sollen, indem Kohlendioxid aus der Atmosphäre entfernt wird. Durch die Entnahme von Kohlendioxid in großem Maßstab könnte dessen Gesamtkonzentration in der Atmosphäre gesenkt werden, was zu einer geringeren globalen Erwärmung führen würde. In der Regel werden diese Technologien als Ergänzung zu konventionellen Emissionsminderungsmaßnahmen betrachtet. Häufig werden CDR-Technologien in drei Bereiche unterteilt: natürliche oder terrestrische, technische und marine CDR. Zu den terrestrischen und technischen CDR-Methoden gehören Bioenergie mit anschließender Abscheidung und geologischer Speicherung des CO_2 (BECCS), direkte Abscheidung von CO_2 aus der Atmosphäre (DAC), Pflanzenkohle, modifizierte bzw. beschleunigte Verwitterung von Gestein und - nach einigen Klassifizierungen - Aufforstung und Wiederaufforstung. Zu den marinen CDR-Methoden (mCDR) hingegen gehören die Wiederherstellung von (Küsten-)Feuchtgebieten (blauer Kohlenstoff), die Erhöhung der Alkalinität, der künstliche Ozeanauftrieb sowie die Eisendüngung. Diese Klassifizierung bleibt unvollständig, ebenso sind weitere Unterteilungen von CDR denkbar. Zahlreiche der vorgeschlagenen Technologien binden Kohlenstoff durch biologische oder industrielle Prozesse an Land und speichern diesen anschließend im oder unter dem Meer, oder umgekehrt. In diesem Diskussionspapier behandeln wir mCDR als eine Reihe von technologischen Ansätzen auf Basis eines Dialogs mit Expert*innen am 1. Dezember 2022.

Seit dem Klimaabkommen von Paris im Jahr 2015 ist die Entnahme von Kohlendioxid zu einem festen Bestandteil der Klimapolitik geworden. Es setzt sich die Ansicht durch, dass CDR-Technologien erforderlich sind, um die 1,5°C- und sogar die 2°C-Ziele zu erreichen, auch wenn es ernsthafte Meinungsverschiedenheiten und Zweifel darüber gibt, inwieweit CDR praktisch umsetzbar oder sozial und politisch wünschenswert ist (IPCC, 2022). Zu einem gewissen Grad stellen CDR-Technologien gar ein wichtiges Mittel dar, mit dem Wissenschaftler*innen und politische Entscheidungsträger*innen die Machbarkeit dieser Klimaziele aufrechterhalten (van Beek et al., 2022). Die meisten klimapolitischen Modellprojektionen sehen eine starke Nutzung von CDR in den kommenden Jahrzehnten vor, obwohl es weit verbreitete Kritik an den zugrunde liegenden Annahmen gibt, die CDR-Technologien in den Modellen attraktiv und vielversprechend erscheinen lassen (z. B. Beck & Oomen, 2021; Carton et al., 2020). Einem Konsensbericht der U.S.-amerikanischen National Academy of Sciences aus dem Jahr 2019 zufolge könnte die sichere und effiziente weltweite Anwendung bestehender CDR-Methoden bis 2050 bis zu 10 Gigatonnen (Gt) CO2 pro Jahr und bis 2100 eventuell sogar bis zu 20 Gt binden (NAS, 2019), obwohl diese Zahlen umstritten und ungesichert sind.

CDR ist umstritten und unsicher. Es bestehen nach wie vor erhebliche Fragen zum Gesamtpotenzial von CDR-Technologien (European Academies Science Advisory Council, 2018; IPCC, 2022b; Luderer et al., 2021). Ebenso könnten die wirtschaftlichen Kosten von CDR unerschwinglich sein (Fuss et al., 2018). Neben den Fragen zu Kosten und Potenzialen birgt mCDR im Speziellen auch erhebliche politische und soziale Risiken. Zu den geäußerten Bedenken gehören: das Risiko der Ablenkung von Maßnahmen zur Emissionsminderung (Beck

& Mahony, 2018; Beck & Oomen, 2021), regulatorische Fragen im Zusammenhang mit weitreichenden ozeanischen Infrastrukturen und der Hohen See (Boettcher et al., 2021), Umweltauswirkungen sowie Bedenken hinsichtlich der Überprüfung der Kohlenstoffaufnahme in Meeresökosystemen (IPCC, 2022b, 2022a; National Academies of Sciences, 2022). Die genauen Auswirkungen von CDR-Technologien sind in hohem Maße kontextspezifisch, was bedeutet, dass sie - bis zu einem gewissen Grad - vor der Umsetzung nicht vollständig bekannt sein können.

In einem vom Umweltbundesamt am 1. Dezember 2022 durchgeführten Expert*innengespräch wiesen diese auf die Notwendigkeit klarer und solider Governance- und Bewertungsverfahren für mCDR hin. Dies steht im Zusammenhang mit einer breiteren Anerkennung der Notwendigkeit einer strengen und kritischen Untersuchung der Risiken und des Potenzials von mCDR. Die wichtigsten Erfordernisse für die Bewertung und Regulierung sind die folgenden:

- Die Annahmen, die den Projektionen und Bewertungen der CDR-Potenziale und der Klimapolitik zugrunde liegen, müssen sehr sorgfältig geprüft werden. Während der Ozean potenziell eine wichtige Kohlenstoffsenke darstellt, bleibt das genaue Ausmaß, in dem diese Kapazität sicher, verantwortungsvoll und in großem Maßstab genutzt werden kann, ungewiss.
- Die ökologischen Folgen, die soziale Machbarkeit, die Akzeptanz und die Gerechtigkeit der mCDR-Methoden müssen in die Bewertungsverfahren und in die politischen Prognosen einbezogen werden. Solche Überlegungen wirken sich unweigerlich auf den Umfang und das Ausmaß des mCDR-Potenzials aus.
- Klare Definitionen und Governance-Verfahren für die Berücksichtigung der natürlichen CO2-Aufnahme des Ozeans im Zusammenhang mit CDR sind notwendig. Von besonderer Bedeutung (und Schwierigkeit) ist die Notwendigkeit, zuverlässige Überwachungssysteme für die ozeanische Aufnahme von Kohlendioxid zu entwickeln. Ohne eine solche Überwachung lässt sich der potenzielle Beitrag der mCDR nur schwer abschätzen.
- Auch Governance-Risiken müssen berücksichtigt werden. Abgesehen von Fragen der Ablenkung von der Emissionsminderung und der Zuständigkeit (diffus oder zentral organisiert, direktiv oder marktorientiert) gehören zu diesen Fragen auch solche nach zukunftssicheren Governance-Verfahren, die sich mit der künftigen Stabilität und Governance sowohl der Kohlenstoffabscheidung als auch der Kohlenstoffsenken befassen.

C.2 Summary

Carbon Dioxide Removal (also referred to as negative emissions technologies and greenhouse gas removal, CDR) describes a range of measures and technology proposals designed to counteract anthropogenic climate change by removing carbon dioxide from the atmosphere. By removing carbon dioxide on a large scale, its overall concentration in the atmosphere could be lowered, resulting in less global warming. Typically, these technologies are considered complementary to conventional emission reduction measures. Often, CDR technologies are divided into three areas (natural or terrestrial, engineered, and marine CDR). Terrestrial and engineered CDR methods include bioenergy with carbon capture and storage (BECCS), direct air capture (DAC), biochar, modified weathering or enhanced weathering, and, by some classifications, afforestation and reforestation. Marine CDR (mCDR) methods, on the other hand, include (coastal) wetland restoration (blue carbon), alkalinization, artificial upwelling, and ocean iron fertilization. It is important to note that these classifications are imperfect and other subdivisions are conceivable. Many proposed technologies capture carbon via biological or industrial processes on land and store them in or under the sea, and vice versa. In this discussion paper, we address mCDR as a range of proposed technologies, based on an expert workshop held on 1 December 2022.

Since the 2015 Paris Agreement, carbon dioxide removal has become an integral part of climate policy. There is an emerging view that CDR technologies are needed to achieve the 1.5°C and even 2°C targets, although there are serious disagreements and doubts about the extent to which CDR is practically feasible or socially and politically desirable (IPCC, 2022). To some extent, CDR technologies are even an important means by which scientists and policymakers maintain the feasibility of these climate targets (van Beek et al., 2022). Most climate policy model projections foresee heavy use of CDR in the coming decades, although there is widespread criticism of those underlying assumptions that make CDR technologies appear attractive and promising in models (e.g., Beck & Oomen, 2021; Carton et al., 2020). According to a 2019 consensus report from the National Academy of Sciences, safe and efficient worldwide application of existing CDR methods could sequester up to 10 gigatons (Gt) of CO_2 per year by 2050, and perhaps as much as 20 Gt by 2100 (NAS, 2019), although these numbers are disputed and uncertain.

CDR is controversial and uncertain. Significant questions remain about the overall potential of CDR technologies (European Academies Science Advisory Council, 2018; IPCC, 2022b; Luderer et al., 2021). Similarly, their economic costs of CDR could be prohibitive (Fuss et al., 2018). In addition to questions about cost and potential, mCDR also poses major political and social risks. The expressed concerns include: the risk of mitigation deterrence (Beck & Mahony, 2018; Beck & Oomen, 2021), regulatory questions around large oceanic infrastructures and the high seas (Boettcher et al., 2021), environmental impacts, as well as concerns about monitoring carbon uptake in oceanic environments (IPCC, 2022b, 2022a; National Academies of Sciences, 2022). The exact impacts of CDR technologies are highly context-specific, which means they – to some extent – cannot be fully known before implementation.

In an online conversation with experts convened by the German Environment Agency on 1 December, 2022, experts signalled a need for clear and robust governance and assessment procedures for mCDR. This ties into a wider recognition of a need for both rigorous and critical investigation of the risks and potential of mCDR. Key necessities for assessment and governance signalled the following:

- The assumptions underlying the projections and assessments of CDR potentials and climate policy need to be considered very carefully. While the ocean potentially provides a major carbon sink, the exact extent to which this capacity can be wielded safely, responsibility, and at scale remains uncertain.
- Ecological consequences, social feasibility, acceptance, and justice of mCDR methods will need to be incorporated in assessment procedures and in policy projections. Such considerations will inevitably affect the scope and scale of mCDR potential.
- Clear definitions and governance procedures around accounting for mitigation in relation to CDR are necessary. Of particular importance (and difficulty) is the need to develop reliable monitoring systems for oceanic uptake of carbon dioxide. Without such monitoring, the potential contribution of mCDR is hard to gauge.
- Governance risks also need to be considered. Beyond questions of mitigation deterrence, and questions of responsibility (diffuse or centrally organised, directive or market-based), such

questions include future-proofing governance procedures, addressing questions around the future stability and governance of both carbon capture and carbon sinks.

C.3 Introduction

Expert talks held on 1 December, 2022, convened by the German Environment Agency in collaboration with the Copernicus Institute of Sustainable Development of the University of Utrecht addressed the scientific and technical feasibility of marine carbon dioxide removal (mCDR). Since the 2015 Paris Agreement, CDR has become an integral part of climate policy. There is an emerging view that CDR technologies are needed to achieve the 1.5°C and even 2°C targets. However, there are serious disagreements and doubts about the extent to which CDR is practically feasible or socially and politically desirable (IPCC, 2022). Most climate policy model projections foresee heavy use of CDR in the coming decades, although criticisms abound regarding the assumptions underlying these models, which often present CDR technologies as overly promising (Beck & Mahony, 2018; Beck & Oomen, 2021; Carton et al., 2020; van Beek et al., 2022). Carbon Dioxide Removal (also referred to as negative emissions technologies and greenhouse gas removal) describes a range of measures and technology proposals designed to counteract anthropogenic climate change by removing carbon dioxide from the atmosphere. By removing carbon dioxide on a large scale, its overall concentration in the atmosphere could be lowered, resulting in less global warming. As such, CDR is typically considered as complementary to conventional emission reduction measures. According to a 2019 research agenda of the U.S. National Academy of Sciences, safe and efficient application of existing CDR methods could sequester up to 10 gigatons (Gt) of CO2 annually by 2050, and perhaps as much as 20 Gt by 2100 (National Academies of Sciences, 2019).

CDR comprises a great variety of proposed interventions in the planetary environment. The methods to capture carbon dioxide range from (re-)planting forests to enhancing the absorptive capacity of oceans to geochemical and industrial processes. Likewise, storing the captured carbon would happen in a variety of ways, such as in ecosystems (such as forest), geological formations on land or under the sea, or (to a limited extent) in the built environment. As such, CDR defies neat classification. Often, CDR technologies are divided into three areas (natural or terrestrial, engineered, and marine CDR). Terrestrial and engineered CDR methods include bioenergy with carbon capture and storage (BECCS), direct air capture (DAC), biochar,enhanced weathering, and, by some classifications, afforestation and reforestation. Marine CDR methods, on the other hand, include (coastal) wetland restoration (sometimes classified as (coastal) blue carbon), ocean alkalinity enhancement, artificial upwelling, and ocean iron fertilization. It is important to note that these classifications are imperfect and other subdivisions are conceivable. Many proposed technologies capture carbon via biological or industrial processes on land and store them in or under the sea, and vice versa. Despite the imperfection of such classification, however, this discussion paper adheres to this classification.

In this paper we address marine and oceanic methods of carbon removal, based on the discussions held on 1 December 2022. In a separate discussion paper, we address terrestrial CDR based on a similar workshop held on 26 October 2022. It is important to note from the outset, however, that scientific classifications of such technologies have political consequences, as they co-determine the types of governance systems set up around technologies. As such, the division between these classifications does not always hold up. It also means that classifying CDR methods is a question for governance as much as science, as it influences both political and policy proposals around governing and developing such technologies.

The basic assumption of CDR is that anthropogenic activities can remove CO_2 from the atmosphere and permanently store it in geologic, terrestrial, or oceanic reservoirs. Potentially, CO_2 could even be stored in products through carbon capture and utilization (CCUS), although the overall gain would be limited. All IPCC pathways rely on CDR to offset at least so-called residual or hard-to-avoid emissions. Most also rely on carbon budget overshoot offsets. With 2023 as a base year, the remaining carbon budget to stay below 1.5°C (50% likelihood) is estimated at about 250 gigatons (Gt) of CO_2 emissions while for the 2°C target, the remaining budget would be about 1150 Gt (50% likelihood, Forster et al., 2023). At the current rate of CO2-equivalent emissions of about 57.4 GtC02e per year (United Nations Environment Programme, 2023), the remaining carbon budget for the 1.5°C target in particular might be exhausted rapidly. To meet the climate targets, the models assume substantial use of CDR. As the 6th IPCC report states:

'In modelled pathways that report CDR and that limit warming to 1.5°C (>50%) with no or limited overshoot, global cumulative CDR during 2020-2100 from bioenergy with carbon dioxide capture and storage (BECCS) and direct air carbon dioxide capture and storage (DACCS) is 30-780 GtCO2 and 0-310 GtCO2, respectively. In these modeled pathways, the AFOLU sector contributes 20-400 GtCO2 net negative emissions. Total cumulative net negative CO2 emissions including CDR deployment across all options represented in these modelled pathways are 20-660 GtCO2. In modelled pathways that limit warming to 2°C (>67%), global cumulative CDR during 2020-2100 from BECCS and DACCS is 170-650 GtCO2 and 0-250 GtCO2 respectively, the AFOLU sector contributes 10-250 GtCO2 net negative emissions, and total cumulative net negative CO2 emissions are around 40 [0-290] GtCO2. (high confidence)' (IPCC, 2022b, SPM WGIII: p. 29).

At the same time, the modelled pathways utilize the portfolio of CDR measures in various ways, for example regarding the reliance on BECCS: some pathways that assume a low energy demand and/or a rapid transition to sustainable diets and thus a change in land use towards afforestation forgo the use of BECCS completely or for the most part (IPCC, 2018; van Vuuren et al., 2018).

Overall, CDR is still fraught with controversy and uncertainty. Significant questions remain about the potential of CDR technologies (European Academies Science Advisory Council, 2018; IPCC, 2022b; Luderer et al., 2021), as well as the potential of mCDR in particular (National Academies of Sciences, 2022). Similarly, the economic costs of CDR could be prohibitive (Fuss et al., 2018). The economic viability of CDR is thus heaviliy reliant on carbon pricing, and the form of such pricing, amongst other factors, will influence which CDR methods become economically feasible on a large scale. For many of these technologies, it is unclear how great the potential for expansion is. The IPCC report also acknowledges these uncertainties:

'CDR methods vary in terms of their maturity, removal process, time scale of carbon storage, storage medium, mitigation potential, cost, co-benefits, impacts and risks, and governance requirements (high confidence). Specifically, maturity ranges from lower maturity (e.g., ocean alkalinization) to higher maturity (e.g., reforestation); removal and storage potential ranges from lower potential (3 GtCO2 yr-1, e.g., agroforestry); costs range from lower cost (e.g., USD-45-100 per tCO2 for soil carbon sequestration) to higher cost (e.g., USD100-300 per tCO2 for DACCS) (medium confidence).' (IPCC, 2022b, SPM WGIII: p. 40).

In addition to questions about cost and potential, marine CDR also poses major political and social risks. Many observers have expressed concerns: the risk of mitigation deterrence (Beck & Mahony, 2018; Beck & Oomen, 2021), regulatory questions around large oceanic infrastructures and the high seas (Boettcher et al., 2021)m environmental impacts, as well as concerns about monitoring carbon uptake in oceanic environments (IPCC, 2022b, 2022a; National Academies of

Sciences, 2022). The exact impacts of CDR technologies are highly context-specific, which means they – to some extent – cannot be fully known before implementation.

C.4 CDR and 'Geoengineering'

Until recently, CDR often used to be described as 'geoengineering'. Geoengineering, as a term, historically connoted a wide range of large-scale interventions in the planetary environment. Originally, the term included CDR measures as well as solar radiation techniques. It has enjoyed a wide usage both in relation to anthropogenic climate change (e.g. National Academies of Sciences, 2021; National Academy of the Sciences, 1992; Royal Society, 2009; Umweltbundesamt, 2011) and lithosphere geoengineering (e.g. Civil Engineering Research Foundation [CERF], 1994; Morgenstern, 2000; National Research Council (U.S.), 2006), as well as occasionally in ecology, in relation to treating hypoxic dead zones in seas and lakes (Lürling et al., 2016; Stigebrandt et al., 2015). Although these interventions share a family resemblance in terms of the underlying rationality and aims (Oomen & Meiske, 2021), in the public eye geoengineering has increasingly come to be synonymous with 'climate (geo)engineering'. In relation to climate change, the term geoengineering first appeared alongside an early CDR proposal, which suggested storing CO_2 in thermohaline currents (Marchetti, 1977). Since the mid-2000s, the term 'geoengineering' has increasingly come to be used to along the lines of the Royal Society's 2009 definition of the term: 'deliberate large-scale intervention in the Earth's climate system, in order to moderate global warming' (Royal Society, 2009: ix). The term geoengineering is an umbrella term, connoting a wide range of diverging technologies and interventions. It includes both carbon dioxide removal (CDR), technologies aimed at addressing the root cause of climate change by capturing and storing greenhouse gases in myriad ways, and solar radiation modification (SRM), technologies aimed at masking warming and limiting the direct damage of climate change. This discussion paper is the third in a series of three discussion papers on the issue of 'geoengineering'. They are the precursor to a renewed positioning by the UBA on geoengineering. Since 2009, a series of scientific assessments of geoengineering have been published. In 2009, the Royal Society published the first major report on 'geoengineering', which at the time included both carbon dioxide removal (CDR) methods and SRM. In 2015, the National Academy of Sciences published two reports on the same topic, using the term 'climate intervention. Responding to an increasing demand to treat CDR and SRM separately, the NRC had separate reports for both technological categories (National Research Council, 2015a, 2015b). In 2019, 2021, and 2022, the NAS published three more reports on research strategies for tCDR, SRM, and mCDR (National Academies of Sciences, 2019; 2021, 2022).

In 2011, the UBA published a report on geoengineering, as a broad technological category. Since 2011, much has changed in the political and scientific debate around climate change and geoengineering – although many of the same uncertainties remain. For one, CDR and SRM have become increasingly differentiated, increasingly treated in isolation from one another. As a result, the term 'geoengineering' has also become less common, especially in relation to CDR. In this discussion paper series, we recognise this differentiation, acknowledging both the inevitable imperfection and necessity of classifying geoengineering. This third discussion paper addresses marineCDR (mCDR). In the recent literature, this category often also appears as oceanic CDR (oCDR). The other two papers in the series address SRM and land-based (terrestrial) CDR (tCDR).

A final note on terminology: In the past, CDR technologies were also known through accounting terms such as "negative emissions technologies" (NETs) because they are intended to counteract "positive emissions" (meaning carbon emissions). In addition to CO_2 capture, approaches to capture other greenhouse gases, such as methane, also exist. As a result, both scientists and assessments have also used greenhouse gas removal (GGR) as an umbrella term. In its most recent reports, the IPCC has consistently used the term carbon dioxide removal. As such, this discussion paper will adhere to this usage.

Insights from expert talks

As our expert talks made clear, the need for sizeable CDR implementation is almost universally accepted by climate scientists. However, most worry that CDR leads to **mitigation deterrence**, as it may delay mitigation commitments in the present or lead to high amounts of residual emissions in the future. Moreover, all experts raised questions of governance, monitoring, social feasibility, and acceptance.

In contrast to mitigation measures, CDR measures are immature, have unclear potentials, costs and side effects, unclear controllability. As such, CDR could never take the place of strict mitigation commitments. All experts present in the workshop also favored clear and robust ways to account for the amounts of CDR necessary. Particularly present was the worry that CDR would not be used to offset hard to abate emissions but for emissions that should have been mitigated. Moreover, several experts highlighted a tendency to overestimate the costs of mitigation while underestimating the economic and social benefits of a successful energy transition, as well as underestimating the true costs of CDR.

C.5 Marine Carbon Dioxide Removal: the Technologies

In recent years, mCDR has attracted increasing attention. Kari de Pryck and Miranda Boettcher note that the UN Special Envoy for the Ocean, Peter Thompson, summed up this increasing interest in mCDR as follows: "the global conversation is now moving toward oCDR. The risks and costs of oCDR are glaring and we remain very deficient in our global knowledge and decisions on this subject. So, for better or worse, CDR will alter planetary conditions" (as cited in De Pryck & Boettcher, 2024, p. 1). Marine CDR, as an area of investigation, starts from the simple observation that oceans are the largest carbon sink on the planet, with oceans covering around 70 percent of the Earth's surface. As the US National Academic of the Sciences (NAS) observed in their recent report on a research strategy for mCDR,

"*the ocean holds great potential for uptake and longer-term sequestration of anthropogenic CO2 for several reasons: (1) the ocean acts as a large natural reservoir for* CO_2*, holding roughly 50 times as much inorganic carbon as the preindustrial atmosphere; (2) the ocean already removes a substantial fraction of the excess atmospheric* CO_2 *resulting from human emissions; and (3) a number of physical, geochemical, and biological processes are known to influence air–sea* CO_2 *gas exchange and ocean carbon storage*" (National Academies of Sciences, 2022, p. 2).

Given the potential of marine systems to capture and store large amounts of carbon, it is unsurprising that scientists are looking to study and amplify this capacity in a safe and ecologically sound manner. That being said, mCDR remains a contested field, with a long and complicated history (De Pryck & Boettcher, 2024). De Pryck and Boettcher observe that early ideas in a similar vein already emerged in the 1960s. In the climate debate, mCDR increasingly took centre stage since 2014, when ocean-based sequestration increasingly became constructed as a necessity. Despite this longer history, however, many technical, geopolitical, and socioeconomic uncertainties remain. There are major differences between its technologies, in terms of its technical, ecological, geopolitical, and socioeconomic risks.

A range of mCDR proposals exists (see figure 1). In 2022, the National Academy of the Sciences (NAS) issued a report on the state of research and the need for a comprehensive research agenda for mCDR. The technologies they selected include ocean fertilization, alkalinity enhancement (including enhanced weathering), electrochemical approaches, and restoration of marine and coastal ecosystems. As the report noted, there are major differences in the potential scope and durability of these methods. Here, we single out some of the major proposals, including their potentials, although this selection is not definitive: For example, Carbon Capture and Storage (CCS) is sometimes categorized as a form of "marine CDR," although the capture processes, such as through bioenergy (BECCS) or Direct Air Capture (DAC), are primarily land-based. For more details on the integration CCS into its integration into national climate action strategies, refer to the UBA position paper on CCS (UBA, 2023).

C.5.1 Ocean fertilization

Some of the methods discussed relate to increasing biological productivity in the ocean. Most prominently, ocean fertilization proposes to add macro- and micronutrients, especially iron, to the ocean surface to stimulate the photosynthesis of marine phytoplankton under certain conditions. The exact CDR potential of ocean fertilization remains unclear, but the National Academy of Sciences (NAS) estimates it to be >0.1–1.0 Gt CO_2/Yr. The IPCC cites an annual potential of 1–3 Gt CO_2 (Babiker et al., 2022) specifically for iron fertilization. The potential of macro- and micronutrients is often evaluated differently– with the potential of macronutrient fertilization considered to be significantly greater than that with iron, for example (Gattuso et al., 2021). However, the use of iron would be characterized by the need for only small quantities (National Academies of Sciences, 2021). In essence, ocean fertilization suggests to strength the ocean's biological carbon pump, which allows carbon dioxide to be transported to the deep sea and stored there for periods of a century or more. The effectiveness of the method would vary greatly depending on the region of application due to different nutrient concentrations and thus achieve saturation at different rates (Hauck et al., 2016). Like all mCDR proposals, ocean fertilization is not without risks. Specifically, it risks significant ecological impacts, some of which are difficult to assess: upper and deeper ocean layers could be affected by oxygen deficiency in the event of eutrophication; the effects on food chains are unclear (Honegger et al., 2018; National Academies of Sciences, 2021). Furthermore, short-term positive effects on the acidification of upper ocean layers contrasts with long-term negative effects of the CO_2 release in the lower layers (Oschlies et al., 2010, Gattuso et al., 2021).

C.5.2 Artificial Upwelling & Artificial Downwelling

A second method that aims to harness increased biological productivity is artificial upwelling. In this process, cooler and CO_2-rich water from deeper ocean layers would be pumped to the surface to stimulate primary production and consequently CO_2 uptake. There are considerable uncertainties, such as a disturbed interaction with the natural carbon pump as well as the unintentional release of CO_2 from deeper layers (Gattuso et al., 2021; National Academies of Sciences, 2021). A cooling effect on the atmosphere, reduced precipitation, and ocean acidification are other potential effects discussed in the literature (Keller et al., 2014). With the increasing warming of deeper ocean layers, the cooling effect would diminish; moreover, this method is associated with a high risk of a termination shock (Oschlies et al., 2010, Keller et al., 2014). The possible uses are considered to be locally limited (Gattuso et al., 2021; National Academies of Sciences, 2021).

Artificial downwelling, on the other hand, is the transport of water from the surface to deeper layers. Its original ideas was to control eutrophication and low oxygen concentrations (hypoxia) locally, but it may also be possible to reduce the risk of unwanted CO_2 escape through artificial downwelling. However, cost factors and technological uncertainties call into question its feasibility (National Academies of Sciences, 2022).

Insights from expert talks

In the expert discussions, artificial upwelling was described as a measure with great theoretical potential, but also as a risky option. Artificial upwelling is invasive and may have a major ecological impact. The atmosphere could cool down considerably, particularly in the regions where it is used. According to the experts, the greatest danger lies in the possibility of a termination shock, as the interruption of the measure could lead to catastrophic consequences. In addition, the reduction in oxygen content and oxygen uptake could lead to anoxic regions. From a broader perspective, however, the redistribution of nutrients could also lead to ethical questions about the winners and losers of the intervention.

C.5.3 Ocean alkalinity enhancement

Ocean alkalinity enhancement (OAE) proposes to increase the ocean's capacity to absorb carbon dioxide by changing its chemical composition. By adding minerals or drawing on enhanced weathering techniques, a more alkaline ocean would be capable of absorbing more carbon dioxide directly from the atmosphere. Potentially, carbon sequestration via ocean alkalinity enhancement might range from >0.1-1.0 Gt CO_2/year (National Academies of Sciences, 2021). It would also have the added benefit of combating ocean acidification, a key negative consequence of rising carbon dioxide levels.

Technologically, alkalinization methods rely on enhanced weathering, strengthening the natural process of mineral dissolution by seeding the ocean with large quantities of alkaline powdered rock. This would primarily include dissolving naturally occurring silicate-based minerals (such as olivine), the accelerated weathering of limestone, and the dissolution of calcium carbonate derivatives. In addition to numerous technical questions – such as the necessary particle size or the method of implementation – ocean alkalinization present many questions of permanence. If CO_2 can be converted stably into other inorganic carbon molecules, such permanence might be guaranteed, but there remains uncertainty about possible disruptive factors such as ocean currents or a high concentration of phytoplankton (National Academies of Sciences, 2021). Logistical challenges, sociopolitical, and environmental costs of the mineral mining required for alkalinization also represent considerable uncertainties.

The effects of OAE on marine biomes are still largely unknown, although they likely depend strongly on the minerals used (Babiker et al., 2022). This also pertains to a potential release of toxic trace metals (Hartmann et al., 2013). Knowledge gaps also remain regarding the effect of a large-scale alkalinity increase on calcifying organisms. Potentially, alkalinization could protect vulnerable ecosystems – such as coral reefs – from ocean acidification. However, there may be a risk of a termination effect if OAE should suddenly be ended (Babiker et al., 2022).

Insights from expert talks

In the expert discussions, enhanced weathering in particular was discussed as a method of increasing alkalinity. The experts saw marine enhanced weathering as a presumably costly method with great potential. They saw the greatest challenges, like with practically any geoengineering and mCDR technologies, in the infrastructures needed to implement enhanced weathering at the projected scales. Specifically, logistics of unlocking mining capacity for the method seemed an issue, although the use of industrial waste such as residues from the cement industry could be considered. Although, overall, negative ecological effects were deemed manageable, the question of ocean fertilization was discussed, as this could change ecosystems in an as yet unknown way. Additionally, some experts raised the concern that alkalinization using olivine might lead to a dangerous increase in heavy metals and its corollary poisoning effects in ecosystems. As such, alternative chemicals, such as chalk, might be safer options.With regard to the short and long-term biogeochemical side effects, but also possible co-benefits, further research was therefore called for.

C.5.4 Electrochemical Approaches

Another potential method targeting the alkalinity of seawater are electrochemical options that use electricity to drive chemical reactions, for example by running an electric current through isolated ocean water to change its acidity or by the forced separation of solid alkaline substances (La Plante et al., 2021; National Academies of Sciences, 2021). Electrochemical approaches for direct CO_2 removal are also being discussed. Some of these approaches would use the creation of acidic conditions around an anode to achieve a higher concentration of aqueous CO_2 for capture and storage. Other approaches would exploit basic conditions around the cathode to achieve a higher concentration of bicarbonate or carbonate ions, creating conditions for corbonate precipitation and, thus, increased aquaeous CO_2 (National Academy of Sciences, 2022). In both approaches, the base and acid streams would then be reunited and could be returned to the ocean (National Academies of Sciences, 2021).

Potentially, such electrochemical approaches might help capture between 0.1 and 1.0 Gt CO_2/year, with large uncertainties about the potentials. With regard to permanence, approaches that produce mineral carbonate compounds in particular promise to permanently bind CO_2 without the risk of leakage (La Plante et al., 2021). It is conceivable to use any by-products of electrochemical processes, including hydrogen, oxygen or minerals. However, if the pH value is adjusted, there is a risk of negative effects on marine organisms locally.

C.5.5 Protection and restoration of marine and coastal ecosystems

In addition to the above-mentioned ideas on marine CDR, the protection and restoration of fish stocks, the protection of whales and other marine animals, as well as the protection and restoration of kelp forests and e.g. brown algae stocks (sargassum) also have potential for CO2 removal and sequestration. These strategies partly fall under the broader category of "blue carbon," which the IPCC (2021) defines as "biologically driven carbon fluxes and storage in marine systems that are amenable to management." It is to be expected that this low- to risk-free approach with numerous co-benefits with biodiversity conservation is desirable, socially acceptable and regulable. Considerable gaps in knowledge on the anthropogenic effect on the CO2 sequestration potentials of marine and coastal ecosystems remain, and CO2-related quantifications of the effect of species protection, protected habitats or fishing quotas are missing. Nevertheless, the NAS (2022) estimates the annual potential of protection and restoration measures at <0.1–1.0 Gt CO2.

C.6 What we (don't) know about mCDR

The expert workshop made clear that mCDR, like tCDR, is a necessary domain of research and development fraught with complications. It is not at all clear what potential of different technologies are, nor how they interact with each other. The estimates for many technologies vary by an order of magnitude or more, even when accounting only for geophysical, bioecological, and technical constraints. When economic considerations and social, political, and justice issues enter the equation such uncertainties compound further. In any case, it is unlikely that mCDR technologies will reach the optimistic potentials as they appear in assessment reports. Even more uncertain is whether they will reach the potential that is assumed in many climate-emissions projections based on integrated assessment modelling (IAM) and corresponding national climate policies. As a recent investigation by Lisette van Beek and colleagues (van Beek et al, 2022) found, many IAM modellers themselves are deeply sceptical about the potential of real-world climate policy to achieve the CDR potentials their models assume. These concerns do not deviate meaningfully from the concerns in the tCDR debate. There is a real risk of overhyping mCDR potentials, as well as underestimating its risks (De Pryck & Boettcher, 2024). As such, it is essential to evaluate mCDR not solely in the context of CO_2 or even climate risk, but also within the broader context of ecological impacts, social feasibility, and issues of justice. The research and implementation of CDR cannot be divorced from these political and social realities, as they will inevitably influence the potential scale and effectiveness of these strategies.

Furthermore, discussions around CDR will naturally occur within the broader context of sustainability politics. These discussions will be shaped by frameworks such as the United Nations Sustainable Development Goals (SDGs), which will influence how CDR is perceived, prioritized, and integrated into global sustainability efforts (s. chapter 4 of the main report). An assessment of the potential interplay between mCDR and the targets expressed by the SDGs is complex: For one, a deployment interacts with all SDGs affected by the progression of climate change, such as SDG 1 (No Poverty), SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-being), SDG 6 (Clean Water and sanitation), SDG 14 (Life Below Water), and SDG 15 (Life on Land). At the same time, the concern around mitigation deterrence through a reliance on mCDR technologies would invariably impact SDG 13 (Climate Action) and interact with all other SDGs through their relation to climate change (Boettcher et al., 2021).

Beyond this crucial connex, the interactions with the SDGs depend on the specific mCDR method. The environmental and CO2 emission impacts of mCDR's macronutrient use in **ocean fertilization** must be critically assessed, given its high energy and material expenditure. While this process could compete with agricultural fertilizers and adversely affect food security (SDG 2, Zero Hunger), the risk may be lower if iron is used as the macronutrient (Honegger et al., 2018). **Artificial upwelling** offers potential benefits by enhancing fish stocks and aquaculture, thereby contributing to CO2 sequestration and improving food security (SDG 2, Zero Hunger) (National Academies of Sciences, 2021). However, this method also carries risks, including altered precipitation patterns and ocean acidification, which could negatively impact marine ecosystems (SDG 14, Life Below Water) and food security (SDG 2, Zero Hunger). **Artificial downwelling** could help combat eutrophication, while **ocean alkalinity enhancement** methods**,** despite their potential benefits for marine ecosystems (SDG 14, Life Below Water) by counteracting acidification (Feng et al., 2016; Gattuso et al., 2018), also pose health risks from dust pollution during mineral mining (SDG 3, Good Health and Well-Being). Moreover, regional variations in alkalinity increases might lead to harmful chemical changes in seawater, further stressing ecosystems (National Academies of Sciences, 2021; Bach et al., 2019). Beyond CO2 removal, efforts towards the **protection and restoration of marine and coastal ecosystems** are expected to generate co-benefits across several SDGs, such as improved water quality (SDG 6, Clean Water and Sanitation), urban flood protection, and better air quality (SDG 3, Good Health and Well-Being). However, these efforts may also lead to trade-offs with agricultural and aquaculture activities, potentially jeopardizing local poverty reduction (SDG 1, No Poverty) and food security (SDG 2, Zero Hunger), and posing significant political challenges (Honegger et al., 2021). A cross-technology governance challenge lies in ensuring participatory and democratic implementation (SDG 16, Peace, Justice, and Strong Institutions; SDG 10, Reduced Inequalities).

Insights from expert talks

In the expert discussions, the paucity of knowledge regarding the interference of mCDR with marine ecosystems was discussed. The uncertainties surrounding enhanced weathering, fertilization effects and the massive interference caused by upwelling and downwelling stood out in particular. It was emphasized that field experiments should further investigate the effects on biota. However, some certainty was expressed regarding the differences in the ecological impact of mCDR options, with enhanced weathering or alkalinity enhancement likely to be less problematic than upwelling. With regard to the restoration of coastal ecosystems, reference was made to existing differentiated findings on ecological and social risks and possible co-benefits.

These interactions with the SDGs underscore the deep uncertainties surrounding the use of mCDR technologies. Much like other CDR methods, mCDR's impacts on the goals expressed by frameworks such as the SDGs remain speculative, largely because CDR projections are based on theoretical models rather than empirical data. Model projections – while robust and rigorous – may underestimate real world friction, in terms of technological development, public resistance against potential ecological effects, socioeconomic questions around building the required infrastructures as well as geopolitical tensions around the use of oceans as carbon sinks. For instance, in contrast to tCDR methods, mCDR poses specific geopolitical challenges in dealing with the high seas, areas beyond under national jurisdiction regarding the regulating the use of technology (Boettcher et al., 2021). Moreover, as with all carbon capture methods, questions remain about the permanence of CO2 storage, including the potential of leakage.

Another uncertain dimension concerns an ideal versus a realistic coordination of removal targets by mCDR, which also needs to safeguard CO2 reduction targets. In general, international coordination was considered ideal but unrealistic by experts, with national removal targets appearing more feasible and verifiable. As one approach to the issue of mitigation deterrence, the need to keep the accounting of emissions reduction and CO_2 removal separate was discussed.

In short, the same uncertainties apply here as those addressed in the tCDR report (s. Annex B): Numerous calculations of CDR assume the technologies will serve to remove so-called residual, or hard-to-abate emissions. In other terms, CDR would come into play as soon as and insofar as emission reduction is considered too costly or infeasible after a certain point in time. This assumption, however, drew some criticism during the expert discussions. The specification of the socially acceptable remaining amount of emissions cannot be made objectively. The potential and use of CDR would thus become an object of political negotiation, which might lead to mitigation deterrence - such as in the form of delaying tactics, pointing to alternatives, or overestimating the costs of emissions avoidance. Moreover, setting a transitional time limit between a climate policy of emissions reduction and CDR might create a time trap in that any emissions remaining at a fixed point in time would default to CDR. Conversely, this limit could jeopardize the inclusion of CDR measures in earlier climate policy portfolios. Given the political risks attached to the narrative around CDR as a top-up mechanism for incomplete emissions reductions, the fundamental assumptions of CDR and their potential implications must be scrutinized.

C.7 Conclusion

Since the German Environment Agency's last report on geoengineering, the world of climate politics has changed dramatically. As a result, the status of mCDR as a potential approach to climate change has also changed. Carbon dioxide removal is now a key assumption of virtually all modelled scenarios for the future of climate change that are compatible with climate targets. In a complex dance between science, politics, and policy, CDR has come to be perceived as both necessary and inevitable (Carton et al., 2020; Stoddard et al., 2021; van Beek et al., 2020, 2022). In its slipstream, the hype – in the sense of a risk of overpromising its potential – of mCDR has also increased (De Pryck & Boettcher, 2024). Increasingly, mCDR is shedding the label geoengineering, and becoming (in public and political perception) a rather conventional form of climate mitigation. Blue carbon promises that rely on the restoration of coastal ecosystems, for example, have become booming business (Ertör & Hadjimichael, 2020). It promises now include a CO2 sequestration of 0.02–0.08 Gt per year (Babiker et al., 2022). At the same time, the monitoring of such promises remains challenging (Mengis et al., 2023). This political reliance on CDR, both terrestrial and oceanic, is not without risks. Considerable scientific uncertainty and disagreement still exists about the extent to which CDR can live up to its promises. Although there is an emerging view that mCDR may contribute considerably to counteracting climate change, most scientists also advice caution, especially as the promise of mCDR as it appears in models might be overestimated (Boettcher et al., 2021). At the same time, the specific set of possible risks and synergies beyond the potential for CO2 removal alone, including any interactions with the Sustainable Development Goals, are contingent upon the specific method of mCDR.

From our expert discussion, it became clear that experts converge on several issues that pertain to CDR as a whole, as well as some that relate to mCDR in particular. First and foremost, for all kinds of CDR, a careful, critical, and society-oriented technological development is necessary and desirable. Secondly, CDR should be scaled up and implemented as soon as it is possible to do so in robust and fair ways. At the same time, potential ecological risks and climatic drawbacks of these technologies should not be underestimated. The potential for CDR technologies should not be overestimated – overhyping these technologies is a real risk. Thirdly, public opinion about different forms of technology should be taken seriously, as it will affect their potential for scale-up. Finally, and most importantly, all CDR experts present in the workshop recognised the need for comprehensive and critical forms of CDR governance and assessment. Throughout the workshop, the key necessities for assessment and governance were the following:

- The **assumptions** underlying the projections and assessments of CDR potentials and climate policy need to be considered very carefully. For example, the **assumptions** made about ecological consequences, social feasibility, acceptance, and justice of mCDR methods will need to be incorporated in assessment procedures and in policy projections. Such considerations will inevitably affect the scope and scale of mCDR potential. As such, there is a need for both larger scale assessments of CDR potentials including such considerations, as a careful investigation and monitoring
- **Monitoring of mCDR implementation is crucial**, and remains an open question. It might prove prohibitive to account for carbon storage reliably, especially in a world in which speculative promises, the technical difficulty of monitoring carbon storage, and shady

business practices intermingle. While this is definitely also a concern for tCDR, the sheer inaccessibility of marine ecosystems may introduce an extra layer of difficulty for mCDR.

- **Clear definitions and governance procedures** around accounting for mitigation in relation to CDR are necessary. Several experts argued for an accounting system that separates CDR from mitigation, to ensure that carbon accounting does not allow CDR to compensate for relatively easily abated emissions.
- **Governance risks** also need to be considered. Beyond questions of mitigation deterrence, questions of responsibility (diffuse or centrally organised, directive or market-based), such questions include **future-proofing** governance procedures, addressing questions around the future stability and governance of both carbon capture and carbon sinks.

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C.9 Agenda

Experts: Dr. Sonja Geilert, Dr. Nadine Mengis, Dr. Miranda Boettcher, Prof. Dr. Andreas Oschlies, Prof. Dr. Martin Zimmer, Prof. Dr. Klaus Wallmann

4 sessions of 60-90 minutes each:

What is mCDR? Technical promises: state of knowledge, development and uncertainties, effects of CDR in climate and ecosystem(s)

Geoengineering in Context: Research Landscape & Funding, Costs, Climate Protection & Governance Implications for UBA

C.9.1 09:00-10:00: Session 1: Introduction & Marine Alkalinity Enhancement

In this first session, there will be a round of introductions before Dr. Sonja Geilert discusses the alkalization of the sea through increased weathering.

Opening by Dr. Jeroen Oomen

Presentation of the experts

Dr. Sonja Geilert: *Marine alkalinity enhancement through accelerated weathering - a possible CDR method?*

C.9.2 10:30-12:00: Session 2: Evaluation of mCDR: Approach, Promises, and Pitfalls

In this second session, we'll look at mCDR from an overarching angle. Here, we talk about how to assess the potential of mCDR, what mCDR may not offer, and what the biggest risks are. The speakers are Dr. Nadine Mengis and Dr. Miranda Boettcher.

Dr. Nadine Mengis: *Germany's net-zero challenge and the potential contribution of marine CDR options*

Dr. Miranda Boettcher: *Diversification of the (in)feasibility evaluation of mCDR*

C.9.3 13:00-14:30: Session 3: What to do with mCDR? Research, funding and risks

The third session is a mixed session that includes both a more overarching perspective from Prof. Dr. Andreas Oschlies and a specific perspective on ecological risks and considerations from Prof. Dr. Martin Zimmer.

Prof. Dr. Andreas Oschlies: *Presentation of artificial upwelling and other marine CDR options in the context of international research activities and different financing models*

Prof. Martin Zimmer: *(Co-)Benefits and Risks of Blue Carbon Storage in Coastal Ecosystems*

C.9.4 15:00-16:30: Session 4: CO2 storage and general discussion

The final session will include an open discussion between all attendees on what the day's input on mCDR research means for the position of the Federal Environment Agency. How does mCDR relate to climate policy in general? Of particular interest for this discussion is how mCDR might interact with other important policy goals of international politics, such as the SDGs. However, the session will begin with a lecture by Prof. Dr. Klaus Wallman on the opportunities and risks of storing carbon dioxide in geological formations under the North Sea.

Prof. Dr. Klaus Wallmann: *Opportunities and Risks of CO2 Storage in Geological Formations under the North Sea.*