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What could responsible carbon dioxide removal look like in the Netherlands?

An exploratory study with recommendations for research and governance

What could responsible carbon dioxide removal look like in the Netherlands?

An exploratory study with recommendations for research and governance

A report commissioned by Klimaatonderzoek Initiatief Nederland (KIN) and conducted by researchers at the University of Twente, Delft University of Technology, and Deltares

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Table of Contents

Summary *1*

Summary of cross-cutting issues for CDR deployment 2

Defining features of CDR 4

Summary of CDR technique-specific issues: Land-based biological CDR 5

Summary of CDR technique-specific issues: Ocean-based biological CDR 6

Summary of CDR technique-specific issues: (Geo)chemical CDR 7

CDR in the Netherlands 8

Nine key concerns about CDR 9

Recommendations: research needs 12

Recommendations: six principles for responsible CDR governance and research 14

Responsible CDR governance and regulation 14

Introduction *16*

Responsible CDR and CDR research 18

Outline of this report 19

What is CDR? *21*

Uptake of atmospheric CO_2 22

Durable storage of atmospheric carbon 23

Durability—how long is the carbon stored for? 23

Reversal risk—what can cause the stored carbon to be unexpectedly released into the atmosphere? 24

Sink saturation—how much carbon can we put where? 24

"Net removals"—quantifying CDR 24

Box 1—What is global warming potential? 25

The Role of CDR in climate change mitigation 26

Types of CDR *28*

Land-based biological CDR 28

Afforestation, reforestation, and improved forest management 28

Peatlands restoration 29

Agricultural soil carbon storage 30

Biomass with carbon capture and storage (BioCCS/BECCS) 31

Biochar 32

Ocean-based biological CDR 34

Ocean fertilisation 34

Macroalgae cultivation and sinking 34

Marine bioCCS and marine biochar 35

Coastal revegetation and restoration 35
(Geo)chemical CDR 36
Direct air (carbon) capture and storage (DACCS) 36
Enhanced (rock) weathering 37
Ocean alkalinity enhancement 38
Direct ocean carbon capture with storage (DOCCS) 39
Resources that limit CDR deployment *40*
Land 40
Harvested biomass 41
Minerals 42
Energy generation and transmission 42
CO_2 transport and storage infrastructure 43
Monitoring of CDR *45*
Forests 46
Peatlands, wetlands, and coastal restoration 46
Soil carbon 47
Biochar 47
BioCCS 47
DACCS 48
Enhanced weathering 48
Ocean CDR 48
Key ethical concerns for CDR *49*
Climate justice 49
Emissions 'overshoot' and justice 50
Box 2—Why is there so much CDR in IAMs? 51
Box 3—Overshoot or high-emissions world? 52
Mitigation deterrence 52
Procedural justice 53
Existing governance structures and mitigation deterrence risks *54*
Carbon credits and the voluntary carbon market 54
The use of CDR by industry 55
CDR in national and international policy 57
Mitigation deterrence risks in Dutch and European governance 59
Managing liability of CDR risks 60
Public acceptance and perceptions of CDR *61*

Public awareness of CDR and media attention 61
Acceptance of CDR options and psychological predictors 62
Specific concerns 63
Public participation 64
Insights for the Dutch context 64
Stakeholder perceptions on CDR in the Netherlands *66*
On the necessity of carbon dioxide removal technologies 66
Carbon dioxide removal technologies in the Netherlands 66
Monitoring, reporting, and verification 67
Greenwashing concerns 67
Public perception and social acceptance 67
Ethics and social justice 68
Research needs and recommendations *69*
Research needed to reduce uncertainties, trade-offs, and risks of CDR in the Netherlands 69
Research needed to improve clear, open and transparent governance of CDR in the Netherlands 70
Research needed to address ethical aspects of CDR 71
Research needed for to support CDR governance and regulation 72
Research needed to better understand societal needs and concerns 73
Recommendations for responsible governance of CDR deployment and research 74
Four principles for responsible governance of CDR deployment 74
Two principles for responsible CDR research and innovation 75
Final words *77*
Acknowledgement *78*
References *79*

Summary

As existing climate change mitigation efforts continue to fall short, carbon dioxide removal (CDR)— techniques that both actively extract carbon dioxide from the atmosphere and prevent that CO_2 from re-entering the atmosphere—has risen higher on the political agenda, including in the Dutch government's latest National Climate Plan. Organisations such as the Intergovernmental Panel on Climate Change (IPCC) and the Wetenschappelijke Klimaatraad (WKR) argue that large-scale CDR is very likely to be required to achieve a CO_2-neutral society in time and to return from the virtually inevitable 'overshoot' in global temperature rise relative to the targets set in the Paris Agreement. However, the large-scale deployment of CDR techniques also raises many questions, particularly about the potential negative ecological and social impacts and the necessary policy frameworks. This discussion is made more challenging by the wide range of CDR techniques that are in various stages of development, have different resource use profiles, and come with different risks and uncertainties.

This exploratory report, conducted by researchers of the University of Twente, Delft University of Technology and Deltares, commissioned by KIN (Klimaatonderzoek Initiatief Nederland[1]), answers the following central question:

What could responsible CDR governance and research look like in the Netherlands?

This question called for a multi-faceted critical assessment of which forms and configurations of CDR can potentially be deployed in the Netherlands. Therefore, this study assessed a broad set of CDR types to understand their possible benefits and impacts, as well as uncertainties and risks, which were then evaluated in the context of competition for resources within the Netherlands and available techniques for monitoring CDR for risk management. As all technologies exist within a social context, this study also takes a critical eye to the current social and political conditions present in the Netherlands to evaluate what conditions are needed to prevent mitigation deterrence or unjust risks and burdens transfer from CDR upscaling. The report brings together insights from a desk study conducted by researchers holding a wide range of academic expertise (i.e., engineers, social scientists, and philosophers), as well as insights gathered from interviews, written feedback, and a workshop with representatives of government, industry, NGOs, and research institutes. This study also identifies an extensive list of knowledge gaps that need to be filled before a definitive scale of deployable CDR can be quantified. We end with recommendations for policy makers and research program managers.

[1] trans. Climate Research Initiative Netherlands

Summary of cross-cutting issues for CDR deployment	
Readiness	CDR systems are diverse, and many involve components that are currently commercially available. However, due to uncertainties about available resources, security of carbon storage, and technology integration, as well as governance and accounting gaps, no CDR technology is clearly ready for large-scale deployment in the Netherlands. Individual CDR projects are possible in the Netherlands across all types of CDR systems but must be evaluated on a case-by-case basis to assess their specific benefits and risks. It is not yet possible to estimate how much CDR may be available in the future.
Resource availability	The Netherlands is a small, dense country with limited resources available to support large-scale CDR within its borders. • **Land**: Almost all land in the Netherlands is already in use. Any deployment of dedicated land-based CDR or supporting activities (e.g., biomass production, solar energy production) would compete with existing and alternate land uses. • **Biomass**: Additional production of biomass in the Netherlands is limited by available land, as above. The use of imported biomass (e.g., for biochar or BECCS) is possible, but risks transferring ecological and social burdens to the region of cultivation. Applying CCS to existing waste biomass combustion is a lower-risk source of BECCS but its availability may decrease as competition for biomass increases, particularly for higher-value applications (e.g., biomaterials, chemicals, fertiliser) and biomass is used more efficiently over time. • **Energy**: Netherlands has a highly congested electricity grid and competition for additional electricity, as well as heat, remains high from both industrial and consumer actors. • **Minerals**: There are no significant deposits of minerals suitable for enhanced weathering in the Netherlands and therefore would need to be imported, increasing associated transport emissions. • **CO_2 transport and storage infrastructure:** The Netherlands has begun development of CO_2 transport and storage infrastructure, but active injection has not begun. Offshore geologic storage is available, including in the form of depleted oil and gas wells. Assessing future scalability of CO_2 storage will depend on learning-by-doing.
Risks	The greatest risk of CDR is that activities to decrease atmospheric CDR will instead, directly or indirectly, lead to increased warming. These risks arise from uncertainties of predicting net climate benefits and co-impacts, indirect effects from resource-use competition and mitigation deterrence, as well as the potential for stored carbon to re-release into the atmosphere. These risks compound as the scale of CDR increases. Risk management requires rigorous and conservative rules for measuring, reporting, knowledge sharing, and monitoring, as well as liability and contingency planning, all of which needs to be regularly reviewed and revised as knowledge on CDR improves.

Summary of cross-cutting issues for CDR deployment, *cont'd*	
Climate justice	Climate justice frames CDR research and innovation activities, emphasising the importance of international and intergenerational fairness in climate policy, as well as moral conflicts raised by CDR policies between global, regional and local scales. Key ethical concerns with CDR include delaying mitigation, unacceptable side-effects from large-scale implementation, overestimating technical abilities to remove CO_2, and the role of large emitters in benefitting from CDR.
Public acceptance	Public acceptance influences the successfulness of implementation of CDR and should be taken into account during policy development as well as decision making about specific projects.
Key research needs	• Assessing CDR governance and accounting practice to minimize risk of mitigation deterrence, undercounting of negative impacts, and double counting of benefits. • Time and space explicit assessment of risks and benefits, including warming and cooling impacts, as well as resource demand and co-benefits for all CDR techniques. • The interactions of CDR upscaling with other Dutch climate action and resource demand, including technical, economic, and social ramifications as well as potential synergies. • Determining the need for CDR by faithfully determining residual emissions that incorporates both highest possible ambition of emission reduction in conjunction with realistic deployment potentials of CDR.
Governance recommendations	• Dutch climate targets should not rely on a specific quantity of CDR until further research determines a realistic level of availability and scalability. • CDR initiatives should prioritise projects that integrate with existing activities in the Netherlands to reduce risks and resource demand as well as to maximize co-benefits. For land-based biological CDR, ecological soundness should take precedence over maximising carbon storage. • Private partners with track records of substantially contributing to GHG emissions and undermining climate policies should not receive public financing to undertake CDR or be involved in publicly (co)funded CDR research and innovation consortia.

Defining features of CDR

The defining feature of a CDR system is the uptake and storage of atmospheric carbon (that is, carbon dioxide, CO_2) whether via natural processes (e.g., via photosynthesis) or technological ones (e.g., via chemical solvents). Systems that only capture and store fossil carbon from exhaust gas (e.g., CO_2 captured from fossil fuel combustion or cement production) reduce the amount of CO_2 added to the atmosphere, but are not CDR.

Following the IPCC categorisation, CDR activities can be categorized into three main types: Land based biological (including living ecosystem and extracted biomass CDR) ocean-based biological CDR and (geo)chemical CDR:

1. **Land-based biological CDR** involves CO_2 uptake via photosynthesis into ecosystems. Living ecosystem CDR depends on natural, living systems capable of storing carbon in the living biomass and other organic matter. This type of CDR can be further grouped into afforestation and improved forest management, wetlands and peatland restoration, and agricultural soil carbon storage. In contrast, extracted biomass CDR, which is then then harvested and stored elsewhere. This concerns biomass with carbon capture and storage (BioCCS/BECCS), where the biomass is combusted and the resulting CO_2 stored in geologic formations, and the formation of biochar through pyrolyses of biomass which then can be stored in soils or other reservoirs (e.g., burials).
2. **Ocean-based biological CDR** involves extraction of CO_2 from marine surface water via photosynthesis, which allows the ocean to take up more atmospheric CO_2. This can be done through cultivation and sinking of ocean micro- and macro-biomass, which is expected to end up in marine sediment (ocean fertilisation and macroalgae cultivation and sinking) or via the restoration or expansion of coastal vegetation. Ocean-grown biomass can also be harvested and used for bioCCS, with the resulting CO_2 stored in geologic formations.
3. **Geo-chemical CDR** includes terrestrial methods where the direct uptake of gaseous atmospheric CO_2 via physical or chemical methods is concentrated, purified and stored in geological formations (e.g., empty oil and gas fields, saline aquifers)—known as DACCS (direct air (carbon) capture and storage)—and the carbonation of atmospheric CO_2 into unsaturated mineral rocks (e.g., olivine and wollastonite), thereby forming carbonates and bicarbonates, which is then stored in the mineral itself (mineralisation) or dissolved into soils (enhanced weathering). This category also includes analogous methods where the CO_2 is removed from and stored in the ocean, such through spreading alkaline materials (e.g., silicates, carbonates) in the water, which will bind dissolved CO_2 (ocean alkalinity enhancement) or through direct ocean CO_2 capture (DOCCS) using, e.g., electrochemical processes.

Summary of CDR technique-specific issues: Land-based biological CDR					
CDR technique	Readiness	Key resources	Integration potential	Risks	Key research needs
Afforestation, reforestation, and improved forest management	Technically mature practices. Continual management required.	Land; Limited possibility to intensify existing forestry practices.	Co-benefits with biodiversity, soil quality, and local temperature management.	Re-release of stored carbon due to pests, fires, drought, or human activity.	Potentials, risk, profiles and management under changing climatic conditions and competition for resources.
Peatlands restoration	Technically mature practices. Continual management required.	Land; current drained peatlands currently used for agriculture.	Co-benefits with biodiversity and water management, paludiculture.	Methane emissions from re-wetted peatlands; indirect impacts from repurposing of agricultural land.	Timing of climate impacts; Potentials, risk, profiles and management under changing climatic conditions and competition for resources.
Agricultural soil carbon storage	Technically mature practices. Continual management required. Need for knowledge sharing and social uptake.	Land; Can co-site with existing cultivated land.	Impacts on crop yields and supplemental nutrient needs can be positive or negative.	Carbon storage highly sensitive to changes management practices.	Effective measurement and monitoring; Practices to balance carbon storage with other environmental objectives.
Biomass with carbon capture and storage	Component technologies are mature, but system integration not proven at scale. Long infrastructure lead times.	Biomass, CO_2 transport and storage infrastructure.	CCS can be applied to existing waste-to-energy, fermentation and biogas plants.	Technical challenges; CO_2 storage stability; CCS scaling difficulties; climate impact of biomass supply chain; Indirect impacts from biomass imports.	Monitoring and managing direct and indirect impacts from imported biomass use, including non-climate impacts.
Biochar	Technically mature production process, but high uncertainty around decay and durability, monitorability, and co-impacts.	Biomass, Land; Can co-site with existing cultivated land.	Possible positive and/or negative impacts on crop yield, water retention, and nitrogen emissions, varying with specifics of implementation.	Methane emissions during biochar production; Uncertain decay rates; Impacts from soil interactions are difficult; to predict; decreases in local albedo.	Decay under changing climate conditions; soil interactions; monitoring and verification of soil and non-soil storage.

Summary of CDR technique-specific issues: Ocean-based biological CDR					
CDR technique	Readiness	Key resources	Integration potential	Risks	Key research needs
Ocean fertilisation	Limited field trials. Storage of sunk microalgae remains highly uncertain. Currently prohibited by international agreements.	Suitable ocean sites.	Unknown.	Ecosystem disruption; misestimation of climate benefits.	Measuring and monitoring carbon storage; Indirect impacts on ocean ecosystems.
Macroalgae cultivation and Sinking	Macroalgae cultivation is technically mature. Storage of sunk macroalgae remains highly uncertain.	Suitable ocean sites for cultivation.	Unknown.	Ecosystem disruption; misestimation of climate benefits.	Measuring and monitoring carbon storage; Indirect impacts on ocean ecosystems.
Coastal revegetation and restoration	Technically mature practices. Continual management required.	Coastal land and near-shore space.	Co-benefits with biodiversity and flood management.	Mis-estimation of carbon uptake, Re-release of stored carbon due to pests, fires, drought, or human activity.	Potentials, risk, profiles and management under changing climatic conditions and competition for resources.

Summary of CDR technique-specific issues: (Geo)chemical CDR					
CDR technique	Readiness	Key resources	Integration potential	Risks	Key research needs
Direct air carbon capture and storage	First-of-a-kind demonstration-scale technologies available but scalability uncertain, particularly regarding integration with CCS and energy systems.	Energy.	Unknown.	Technical challenges; CO_2 storage stability; CCS scaling difficulties; competition for energy (and water for certain types of DACCS).	Reduction of energy and chemical needs; capture effectiveness with changing weather and climatic conditions.
Enhanced rock weathering	Component technologies are technically mature, but techniques to measure and monitor carbon uptake and storage are still in field trial development.	Energy, Minerals, Land; can co-site with existing cultivated land, as well as other in-use land, mining & transportation infrastructure.	Potential impact on soil quality and crop yields, but highly site-specific.	Mis-estimation of carbon uptake; ecological interactions; health risks from small particulate matter, increased mining efforts, reliance on imports.	Measurement and monitoring of CO_2 uptake; potential ecosystem interactions.
Ocean alkalinity enhancement	Small-scale pilot studies, labwork, and modelling. Real-world carbon uptake and indirect impacts highly uncertain. Currently prohibited by international agreements.	Minerals, energy, mining & transportation infrastructure.	Unknown.	Ecological interactions may disrupt local ecosystems or reduce net climate benefits, increased mining efforts, reliance on imports.	Tracking of mineral dispersion; indirect impacts; separating activity effects from natural processes.
Direct ocean carbon capture and storage	Small-scale demonstration plants in operation.	Energy; coastal access; CO_2 transport and storage infrastructure.	Co-locating with desalination plants allows sharing of infrastructure and energy.	Unknown ecosystem and indirect impacts.	Impact of local climatic conditions; ecosystem impacts.

CDR in the Netherlands

Currently, CDR at scale exists in the Netherlands primarily as afforestation, reforestation, and improved forest management as well as coastal revegetation and restoration. These practices have mainly been implemented with other objectives in mind than carbon sequestration. Especially nature conservation efforts for the purpose of biodiversity increase have been a major driver. Other CDR techniques exist on a negligible scale in the Netherlands, with start-ups and commercial pilot operations as well as research-led proof-of-concept efforts.

Research efforts by other groups have also resulted in advice reports on the application of CDR in the Netherlands. CE Delft has released an extensive analysis on the need, and supply of CDR in the Netherlands (de Vries et al., 2025). In their report, they map the potential for CDR implementation (both technically possible and realistic scenario). This study, together with other literature, has been used by the Dutch scientific Climate Council to advice the Dutch government on CDR policy, which led to the CDR roadmap, proposed by the Netherlands' Ministry of Climate Policy and Green Growth in 2025. This roadmap emphasises the role of CDR as strictly supplementary to emission minimisation and the need for emissions of long-duration greenhouse gases (GHGs) to be compensated with permanent forms of CDR.

Thee Netherlands 2035-2045 Climate Plan envisions that, for CDR, the period towards 2030 is to be the "start-up" phase, focused on the creation of appropriate regulation and markets. Then, 2030-2040 is to be focused on upscaling with CDR deployment envisioned to reach annual removal rates of 20-25 Mt CO_2/year by 2040. These ambitions represent achieving, in the Netherlands alone, 7 to 28 times the current amount of CDR deployed globally, and doing so in just over a decade. This would require an unprecedented level of technological learning and deployment as well as an also-unprecedented level of initiative and cooperation within and between nations for collective global waste management.

It is also important to keep in mind that CDR systems are very diverse. Although many systems involve components that are currently commercially available, there are uncertainties about available resources, security of carbon storage, financial resources and technology integration. In addition, there are governance issues – such as accounting gaps, market-driven expansion and mitigation deterrence. Finally, CDR raises important ethical problems, especially in terms of unfair allocation of climate burdens at the global and intergenerational levels and of lack of inclusion of all those affected by the effects of CDR in the decision-making process. In light of these concerns, no CDR technology is clearly ready for large-scale deployment in the Netherlands. Individual CDR projects are possible across all types of CDR systems but must be evaluated on a case-by-case basis to assess their specific benefits and risks. Moreover, Dutch climate targets should not rely on a specific quantity of CDR until further research determines a realistic level of availability and scalability as it is not possible at present to estimate how much CDR may be available in the future. To reduce risks and resource demand as well as to maximize co-benefits, Dutch CDR initiatives should prioritise projects that integrate with existing activities.

When it comes to scaling CDR in the Netherlands, several risks stand out. First and foremost, the Netherlands is a small and densely populated country with limited resources available to support large-scale CDR within its borders. The Netherlands has a highly congested electricity grid and competition for additional electricity, as well as heat, remains high from the existing and future demand of both industrial and consumer actors. In addition, almost all land is already in use so any deployment of dedicated land-based CDR or supporting activities (e.g., biomass production, solar energy production) would compete with existing and alternate land uses. The use of agricultural residues for biochar or BECCS via applying CCS to existing waste biomass combustion are potential sources of biomass-based CDR, but such availability may decrease as biomass is used more efficiently over time and competition for biogenic carbon increases.

The limited possibilities of CDR at scale here, increases the risk of putting the burden of CDR on countries and communities elsewhere. There are no significant deposits of minerals, for instance, that are suitable for enhanced weathering in the Netherlands and therefore would need to be imported, increasing associated emissions and resource extraction concerns. As additional production of biomass in the Netherlands is limited by available land, for instance, an increase in e.g., biochar or BECCS would come with an increase in the use of imported biomass. This, however, risks transferring ecological and social burdens to the region of cultivation.

And although the Netherlands has begun development of CO_2 transport and storage infrastructure, and there exists offshore geologic storage potential, no CCS facility is operational yet and future scalability of CCS-reliant CDR technologies (i.e., BECCS, DACCS, and DOCCS) is uncertain due to the decades' long difficulty of scaling CCS technology in the first place.

Nine key concerns about CDR

Several concerns around CDR are important to consider when aiming to develop responsible CDR. Understanding the uncertainties and risks raised by these concerns, and how they interact with each other and competing technical, economic, and social processes, represents a key area for further CDR research. First, **the future availability of CDR is unknown**. Most CDR technologies are currently nascent, with many technical and implementation uncertainties that remain to be solved. Also, CDR systems are typically resource intensive, starting with carbon and energy, and may also require large quantities of land, minerals, water, underground CO_2 storage reservoirs and other resources. While some synergies are possible, large-scale CDR will compete with demands for food production and infrastructure, other economic sectors as well as other mitigation and adaptation technologies. Finally, the effectivity of many types of CDR depends on climatic conditions, which are already changing, injecting additional uncertainty into its long-term potential.

Second, **CDR has impacts beyond the reduction of atmospheric GHGs**. While some of these can be positive, such as biodiversity or soil quality improvement, there are many risks of negative impacts. Further, resource requirements can lead not only to competition for resources, but potentially other impacts to ecosystems and human health from the CDR activities, their supply chains, and their wastes. The resource demands and risks of a given CDR activity are specific not only to the type of CDR but the specific siting and configuration of the CDR system.

Third, **mitigation deterrence is a major problem**. For CDR, this is the concern that the prospect of removing CO_2 from the atmosphere later will lead to the delay of meaningful and impactful greenhouse gas emission reduction today. Indeed, based on arguments given and choices made by governmental and industry actors, there is evidence that mitigation is already being deterred by CDR-related arguments and actions, despite frequent emphasis that CDR remains supplemental to emission reductions. If the idea of future CDR reduces near-term emission reductions, climate-related risks and harm increase. Such climate-related risks are amplified by the uncertainty surrounding what scale of future CDR deployment is even plausible, thus also increasing long-term climate-change harms in case the presently envisioned scale of CDR never becomes available.

Fourth, **the duration and security of carbon storage is critical**. Where and in what form the atmospheric carbon is stored is the main determinant of the expected durability of a CDR activity. For example, CO_2 stored in geologic formations aims for indefinite storage, while storage in forests requires continuous management to reduce risks of re-release. From a scientific perspective, any future re-release of stored carbon results in renewed global warming and thus will have to be re-removed if we aim for "net-zero" emissions of greenhouse gases. However, some argue that CDR with storage time-horizons on the order of several decades to a few centuries can provide near-term respite from warming while mitigation efforts are on-going. Different forms of CDR require different forms of management to select suitable storage sites, monitor storage, and prevent (or remediate) re-release. All forms of CDR introduce risks of reversal, which makes emission reductions inherently preferable.

Fifth, we must be able to **track both the amount of atmospheric carbon stored *and* the amount of GHGs emitted by the CDR system**, as well as the resources it requires, both to track progress and to avoid risks of 'greenwashing' by nations or companies. For a given CDR activity, this entails quantifying the net removal: the total amount of atmospheric CO_2 removed and subtracting the total amount of greenhouse gases added to the atmosphere in the processes and supply chains of atmospheric CO_2 uptake and storage, including post-storage processes. Otherwise, we risk that a CDR activity leads to an increase in global warming. This process of greenhouse gas accounting has the challenges of balancing data demands with scientific uncertainties, existing accounting conventions, and administrative burden that vary between types of CDR, with more complex CDR systems (e.g., bioCCS or biochar using imported biomass, ocean CDR) having higher risks of misquantification.

Sixth, **adequate regulatory frameworks for CDR are currently lacking** and would not reliably prevent negative side effects. While the EU's Carbon Removal and Carbon Farming

(CRCF) framework seeks to set minimum quality standards for different CDR activities leveraging existing European regulations, policy goals regarding the use of CDR are leading ahead of efforts to ensure that CDR is coherently embedded in the policy landscape as a whole. Already, the European Union is exploring the inclusion of CRCF-certified credits in its Emissions Trading System (ETS) and is considering the use of international CDR credits, under mechanisms such as Article 6.4 of the Paris Agreement, to offset domestic emissions. Similarly, at the Dutch level, policy discussions increasingly propose CDR as a flexible compliance option, in some cases allowing it to substitute for direct emission reductions, despite its fundamentally different characteristics and uncertainties. The current policy architecture is at odds with the strictly complementary role that the CDR roadmap assigns to CDR in relation to emission reductions.

Seventh, **CDR can create conflicts of distributive justice**. Distributive justice concerns how the benefits and burdens of CDR are shared among different groups, especially across nations, social classes, and generations. There are three main distributive justice issues raised by CDR. The first is the issue of risk transfer to the vulnerable, which is linked to the issue of regional and social inequality: large-scale CDR deployment (especially bioCCS and afforestation) could threaten food security, biodiversity, and access to land and water. In the Netherlands, where land competition is mostly with agriculture, these risks are most likely to affect domestic food production and farmer livelihoods, whereas the use of imported biomass or international CDR credits may transfer risk to low- or middle-income countries and are most likely to fall on the global poor and future generations, who have little say in current policy decisions. The second is the problem of potential benefits to current polluters, such as via allowing offsets or financial windfall from CDR, while shifting risks to others. The third is the problem of intergenerational injustice: relying on future CDR to compensate for delayed action means future generations may face a moral dilemma in which they are forced to choose between extreme CDR deployment (with all its risks, resource demands and uncertainties) and accepting extreme impacts from global warming.

Eighth, **procedural justice is essential in decision-making concerning CDR**. Procedural justice relates to inclusive and fair decision-making processes, ensuring that all stakeholders, and especially affected and marginalized groups, have a voice in climate-related decisions. Currently, fossil fuel actors and other profit-driven stakeholders continue to exert significant influence in the policy space, often shaping outcomes in ways that preserve existing economic structures.

Finally, **public perception and acceptance are important to take into consideration** from democratic and ethical perspectives, but also as they influence the successfulness of CDR implementation. Public awareness of CDR options varies, with many CDR options being rather unknown to the public. Acceptance of CDR options also varies, with CDR options that are considered more "natural", to have fewer side-effects or risks, and that are more familiar to people, having higher acceptance. People tend to have a more positive opinion of CDR when they have more concern about climate change, have more technology optimism, perceive more benefits and less risks of CDR, perceive less tampering with nature and more naturalness of the CDR option, and have more trust in various institutions. Participants in various studies expressed similar concerns as mentioned in this report, including who is

paying the costs, durability of the storage, and negative environmental side-effects. Most studies emphasize the need for organising public engagement in decision-making processes about CDR. Little research has yet been conducted in the Netherlands, which begs the question what the public acceptance for all the specific CDR options and projects would be in the Netherlands, and what its determinants are.

Recommendations: research needs

Five groups of research gaps are identified. While not exhaustive, they focus on the key questions for Dutch governance of CDR. In particular, they do not include the specific technical and scientific uncertainties that remain for each CDR techniques.

1. Research needed to reduce uncertainties, trade-offs, and risks of CDR in the Netherlands

Understanding the potential deployment of CDR in the Netherlands requires understanding the locally available resources and conditions that affect CDR suitability. Research is specifically needed to understand how the climatic features of the Netherlands would affect CDR deployment across CDR types, and in particular account for future climate scenarios. Another unresolved question is how CDR deployment interacts with other land-use transitions. Across all CDR approaches, a key research gap is also the development of consistent and scalable monitoring frameworks that can robustly quantify net carbon removals across heterogeneous systems. Finally, a critical look is needed at the models and metrics we use to evaluate CDR, as well as other climate change mitigation options. Understanding the influence of such assumptions and data sources on model results is a key first step towards more robust and transparent decision-making over CDR.

2. Research needed to improve transparent governance of CDR in the Netherlands

Critical attention is needed to implement a CDR governance structure that explicitly accounts for the risks and uncertainties of CDR and includes societal perspectives by means of stakeholder and citizen engagement of relevant groups. Such governance structures include developing adaptive policy pathways, as well as liability mechanisms, and understanding of which CDR risks are independent or co-dependent. Greater emphasis is also needed on placing CDR in the context of other demands for resources, both in modelling and in policy development, including for other mitigation options, as well as adaptation needs and other societal demand for resources, and how these may change over time. Given restricted availability of resources as well as the heterogeneity of CDR implementation systems, it is important to establish selection criteria for a 'merit order' of CDR opportunities available in the Netherlands that considers local resource availability, local technical and ecological synergies and trade-offs, expected removal rates, costs, and social considerations.

3. Research needed to address ethical aspects of CDR

From an ethical perspective, more research is needed to systematically integrate values and principles into CDR projects and activities, such as autonomy, justice, nonmaleficence, beneficence, informed consent, integrity, and respect for nature. This research needs to be carried out both in relation to CDR research and development and in relation to CDR deployment. Another important point is that the literature on CDR should engage more explicitly and more comprehensively with questions of epistemic plurality and knowledge systems. The framing of "responsible CDR" would not only rely on scientific, technical, and policy-oriented perspectives; there is room to further engage with Indigenous, relational, and situated understandings of human–nature relations, as well as broader questions of epistemic justice and whose knowledge counts in shaping climate futures. In addition, since mitigation deterrence represents one of the most important (ethical) risks of CDR, more research is needed to find the conditions or requirement that would make it possible to avoid or at least mitigate the risk of mitigation deterrence in CDR policies and projects. Finally, more conceptual clarity is needed in scientific, political, and economic discourses on CDR, typically on terms such as "durability" and "residual emissions".

4. Research needed to facilitate responsible CDR governance and regulation

Several important governance questions remain insufficiently addressed and warrant further research. First, research is needed on how residual emissions should be defined, assessed, and governed in ways that are transparent, scientifically robust, and socially legitimate. Second, an important research question relates to CDR governance beyond carbon markets. Further research is also needed into alternative governance models for supporting CDR that do not rely primarily on offsetting or carbon credit markets. Third, more research is required to develop accounting and governance approaches that adequately capture differences between removals, reduction, and avoidance—as well as between different types of removals and greenhouse gas emission—and avoid treating carbon removals as fully equivalent to emissions that were never produced. The fourth research question that needs more scrutiny is related to the geopolitics, political economy, and policy stability of carbon removal. Research is needed on how these dynamics influence CDR governance and how climate ambition can be maintained in changing political contexts. Finally, there is the question as to the power and influence of various actors to delay or block just and effective climate action. More research is needed on the role of vested interests, incumbent industries, and other actors that may influence the development of CDR governance and deployment. It includes examining how different actors shape narratives around residual emissions, offsets, technological optimism, and climate ambition, as well as how power asymmetries affect decision-making processes. This includes how these actors influence accounting and monitoring rules that govern the deployment of CDR technologies, enabling them to displace rather than complement emission reductions. Finally, liability mechanisms need to be designed to ensure that long-term risks of carbon reversal are minimized and any reversals that do occur are both accounted for and rectified with additional removals.

5. Research needed on better understanding societal needs and concerns

In order to increase inclusive and participatory decision making on CDR in the Netherlands, and to better understand under which conditions implementation of CDR projects is acceptable, it is important to understand how diverse audiences (including citizens, local communities, and other affected publics) perceive, evaluate and respond to CDR. This involves understanding audiences' views on CDR options in general, as well as related to specific CDR policies and projects. It is particularly important to understand what underlies publics' needs and concerns and what conditions, if any, can lead to acceptance. More application of participatory methods is needed to empower citizens to actively influence decisions affecting their lives. Media analysis studies analysing how different rationales and frames for conducting CDR, as well how different policies and technical options (including monitoring options) are portrayed, can provide insight on how the topic is discussed in the public domain, which will influence how citizens perceive and evaluate CDR. It is of particular importance also to understand and address the concerns of more vulnerable groups.

Recommendations: six principles for responsible CDR governance and research

Two of the main findings of the report are that (a) there are substantial ecological and political side effects of the insistence on, and possible scaling of, carbon dioxide removal and that (b) current regulatory and responsible research and innovation frameworks fall short of reliably preventing these negative side effects. Many of these shortcomings are bound up with the fact that short-term political and economic considerations often outweigh scientific evidence and ethical considerations in climate policymaking. To address these shortcomings, we propose that policymakers, research funders and researchers endorse the following six principles for responsible CDR governance and responsible CDR research.

Responsible CDR governance and regulation

Our report has assessed the current uncertainties of CDR systems and the risks of ecological harm and mitigation deterrence in public and private sectors. We argue that the Dutch government should explicitly limit such risks by subscribing to the following principles:

1. **Demonstrate maximum mitigation ambition.** This would include the honest consideration of—and serious experimentation with—underrepresented policy measures such as scaling down high-emitting economic sectors, as well as demand reduction and sufficiency measures.
2. **Restrict role of removal in mitigation ambitions to a minimum.** Taken together, current regulation risks enabling an unconstrained expansion of CDR demand driven by private actors. The anticipation of technological fixes whose future availability and impacts are still uncertain creates a high risk of weakening present action to reduce emissions.

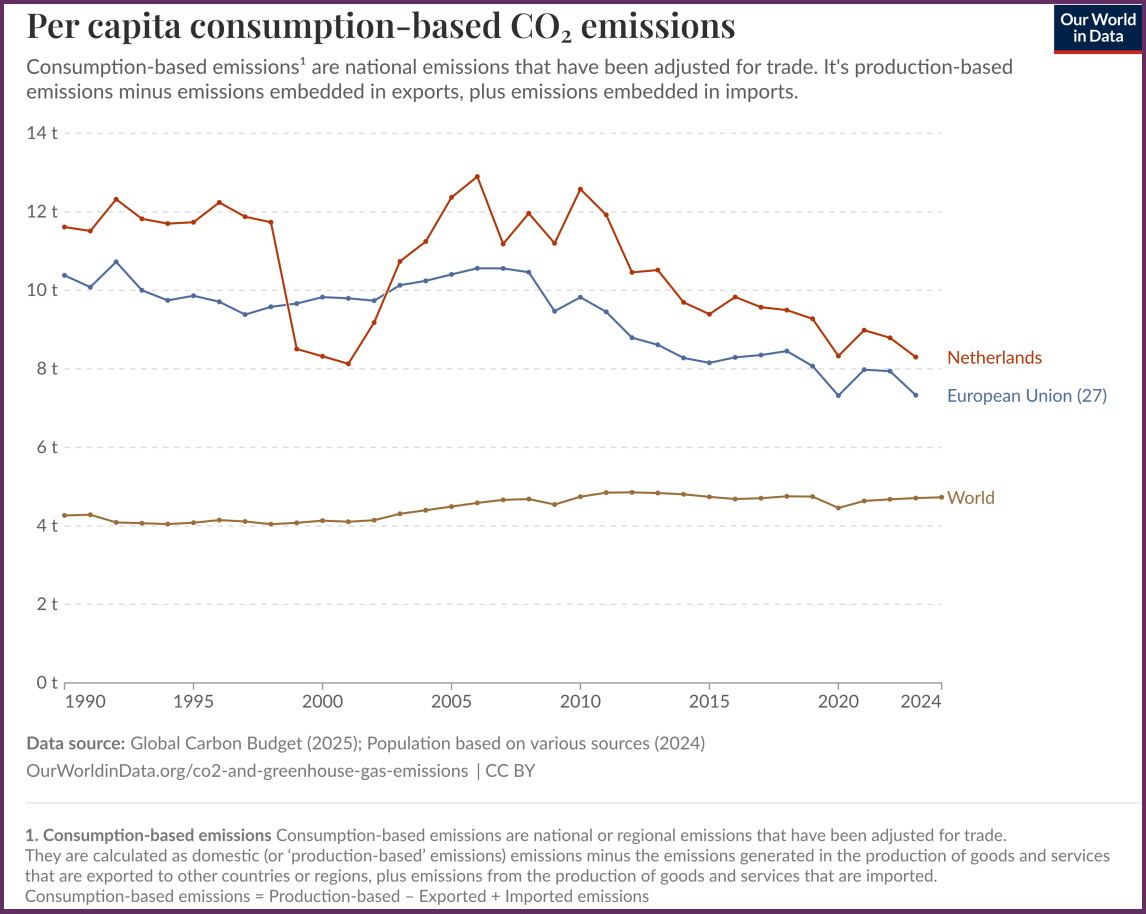
3. **Act out of social and ecological responsibility.** Many of the CDR technologies discussed in this report have significant consequences for land-use and local communities. Both ecological and social justice concerns require thorough consideration of these consequences in the Netherlands and, through export or resource demands, in other parts of the world.
4. **Respect procedural justice.** A responsible approach to CDR governance implies adopting inclusive and equitable decision-making. This requires research into public acceptance, perceptions and concerns, as well as public engagement and co-creation methodologies with local communities and affected groups from the start of the decision-making process, ideally leading to decision-making processes that both include all affected stakeholders, especially vulnerable populations, and enable their meaningful participation on fair terms. Responsible research and innovation

The ethics of CDR—and climate justice more generally—not only concerns responsible governance and regulation, but also has clear implications for the funding of research and public-private partnerships that may be supported through such funding. Based on the findings of our report, we argue that funding transparency – e.g., publicly disclosing which actors contribute to CDR research – is a necessary but insufficient measure to ensure responsible research and innovation. We argue for two additional principles:

5. **Responsible research funding.** Plans to fund research and innovation on CDR should not compete with existing funding for mitigation. Further, given the current technical and systemic uncertainties of CDR, funding for CDR research should also be predicated on transparent and public reporting of all findings and underlying data, which should be synthesized into the larger context of ecological and social impacts.
6. **Responsible research collaboration.** To limit mitigation deterrence risks, those private partners that have track records of (1) substantially contributing to GHG emissions and (2) undermining climate policies should not receive public financing to undertake CDR or be involved in publicly (co)funded CDR research and innovation consortia. Accordingly, fossil fuel extraction companies with a track record of climate policy obstruction would be ineligible for public funding. By contrast, companies with limited past and present GHG emissions, companies rapidly moving away from fossil fuel investment, and/or companies with no record of climate policy obstruction could participate in public-private CDR initiatives.

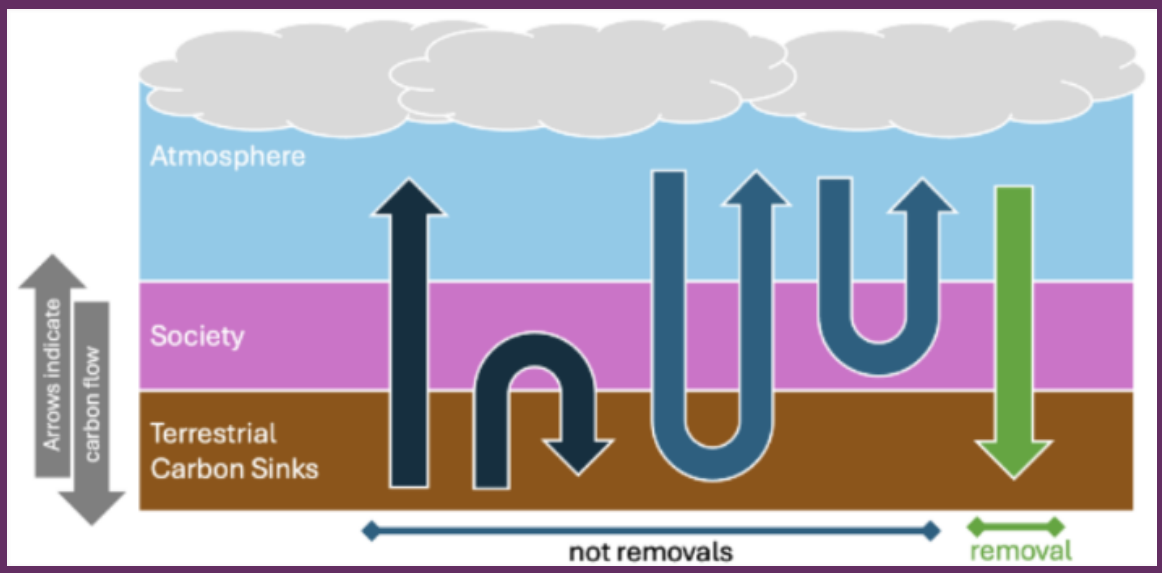
Introduction

Human society has emitted over 1.8 trillion tonnes of fossil carbon dioxide since the industrial revolution, and we continue to emit increasing amounts every year, almost 40 Gt of CO_2 in 2025 along with 16 Gt CO_2-equivalent of other greenhouse gases (GHGs). These emissions have led to an increasing destabilisation of climate systems on which we rely for our survival, and thus an increasing urgency to curtail the risk of catastrophic climate change. Doing so requires that we, first and foremost, dramatically and quickly minimise the amount of GHG we emit. However, when governments and companies continue to fall short on climate action, it becomes possible that we may also have to consider the active removal of GHGs from the atmosphere—a proposition called carbon dioxide removal. But to what extent carbon dioxide removal will be available to us remains an open question.



Dutch emissions in context. The Netherlands emitted 147.2 Mt CO_2eq of greenhouse gases, of which 114.8 Mt were CO_2, within its borders in 2024. However, understanding the country's emissions also requires considering the size of its population and emissions generated in other countries for goods and services consumed in the Netherlands. While its total consumption-based emissions have declined 35% since their peak in 2006, the Netherlands is responsible for 8.3 tonnes of CO_2 per year per person—almost double the global average. Note that this metric also excludes non-CO_2 fossil fuels, which account for 30% of global warming, as well as emissions from international aviation, which accounted for almost 600 kg CO_2 per capita in NL in 2024 (OWID, 2025).

Carbon dioxide removal (CDR), as defined by the Intergovernmental Panel on Climate Change (IPCC) consists of deliberate human "activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products" (IPCC, 2023). However, CDR is an umbrella term for a broad spectrum of systems with diverse uptake mechanisms, carbon transformation pathways and storage options, leading to a corresponding diversity in CDR systems' resource demands, monitorability, expected storage duration and uncertainties. These, in turn, influence their scalability potential, for which further considerations such as cost, possible deployment speed and scale, and failure risks must also be included.



Conceptualizing CDR. Carbon dioxide removal requires both an atmospheric source of carbon and a terrestrial sink in which that atmospheric carbon is then stored. Processes that only involve fossil carbon, or result in the re-emission of atmospheric carbon are not CDR.

The Dutch national government is actively considering the role of CDR in its climate policy, with a "Routekaart Koolstofverwijdering" ("CDR Roadmap") presented to parliament alongside the 2025-2035 Climate Plan. In particular, the 2025-2035 climate plan proposes the role of long-term CDR as a balancing action for residual emissions (estimated with high uncertainty at between 10-40 Mt CO_2eq/year in 2050) as well as a Dutch CDR contribution for historical emissions or in the case of warming overshoot. The plan acknowledges that CDR policy and technology are still in their infancy and in need of development. As an interim target, the climate plan specifies a goal of 20-25 Mt/year CDR between 2040-2050. Before 2030, the Plan envisions a focus on promoting technological innovation and regulation development, with a market-based "scale up" phase from 2030-2040 (Rijksoverheid, 2025).

The plan states five principles for further policy development:

1. Prioritising emission reductions to minimise CDR reliance.
2. Balancing long-lived GHGs with permanent CDR.
3. Only using CDR with "robust methodologies and accounting".
4. Aligning CDR with other policy goals.
5. Preferencing policy roll-out at the European and global level.

However, CDR as a climate change mitigation activity currently globally only exists on a negligible scale. Atmospheric CO_2 uptake and storage by human activities is incidental to their original purposes[2]—such as the use of biochar as soil improver or managed forestry stocks for the production of harvested wood products—and therefore does not speak to the feasibility of dedicated CDR deployment. Excluding forests, CDR accounted for less than 1.4 Mt of atmospheric carbon storage globally, almost exclusively from BioCCS and biochar, with a single bioCCS installation accounting for a third of the estimated gross removals (Smith et al, 2024). However, these estimates do not include the GHGs emitted in the CDR supply chains, so the net climate benefit is lower. Yet the Dutch ambitions alone are to achieve 7 to28 times the current global deployment levels in just over a decade. This would require an unprecedented level of technological learning and deployment as well as an also-unprecedented level of initiative and cooperation within and between nations for collective global waste management. The success of large-scale CDR is deeply uncertain, not only for reasons of technological and climate science, but also for reasons of economics and politics.

Responsible CDR and CDR research

As this report will make clear, many technical uncertainties still surround CDR systems, ranging from resource demand, carbon and energy efficiency, storage duration, and monitorability. These uncertainties compound both within a CDR system and when considering CDR deployment at scale, where considerations of reversal risk and resource competition become more prominent. These, in turn, lead to governance concerns: both ensuring that CDR has the benefits expected of it, while managing risks and liability as well as deploying CDR in a manner that is just and fair to those affected by it, both here and now and in distant geographies and generations. Climate action also has an ecological dimension. Climate change harms ecosystems, species and ecological processes that cannot represent their own interests in policy decisions, but on which human and non-human life

[2] The State of CDR Report 2026 (Edwards et al, 2026) estimates that 2.2 Gt of atmospheric CO_2 was taken up by afforestation/reforestation and managed forestry in 2023, an amount that has been stable for the past two decades and has recently started to decline. Note that this accounts only for CO_2 uptake and not associated GHG emissions, so net removals will be lower.

both depend. This report therefore also considers CDR in terms of whether it can contribute to a safer climate system while avoiding harm to ecosystems, biodiversity and future generations.

As the section on ethical and societal concerns will make clear in more depth, a core concern for the governance and regulation of carbon dioxide removal technologies is that it deflects efforts to reduce greenhouse gas emissions here and now. What if the very prospect of removing CO_2 from the atmosphere later leads to the delay of meaningful and impactful climate action today? When that is the case, the promise of future removals—regardless of their future success—harms the broad societal transformation required to phase out coal, oil and gas and reduce process emissions from agriculture and cement production.

This concept of '**mitigation deterrence'** covers such instances of "reduced or delayed mitigation resulting from the introduction or consideration of another climate intervention" (Markussen et al, 2018). The ethics of CDR, climate justice more generally, and the mitigation deterrence of political and business actors more in particular, have clear implications for the funding of research on CDR as well as public-private partnerships that may or may not be supported or incentivised through public financing.

Research on public acceptance also provides initial insights into how people evaluate and perceive CDR, which could and should be taken into account during policy development as well as decision making about specific projects. Studies suggest that some approaches (for example afforestation, reforestation) are considered more acceptable than more technical or chemical approaches. However, these perceptions should be balanced against other ethical considerations. Furthermore, acceptance, perception, and concerns vary between technologies, locations, groups of people, and how they have been approached and informed.

Outline of this report

CDR deployment is a muti-faceted challenge facing uncertainties of scientific understanding of physical systems, technical development and integration, competition with other climate action and demand for resources, and concerns about risk-sharking and inclusion. Therefore, this exploratory study, conducted by researchers of the University of Twente, Delft University of Technology, and Deltares, commissioned by KIN (Klimaatonderzoek Initiatief Nederland), works to answer the following central question:

What could responsible CDR governance and CDR research look like in the Netherlands?
To do so, the report is organized as follows:

1. **What is CDR** explains the basic concepts underpinning CDR, including both the physical mechanisms of removals and how it fits into climate action more broadly.
2. **Types of CDR** describes a diverse set of CDR systems, highlighting potential risks, co-benefits, key trade-offs, and uncertainties that would need to be addressed prior to their deployment.

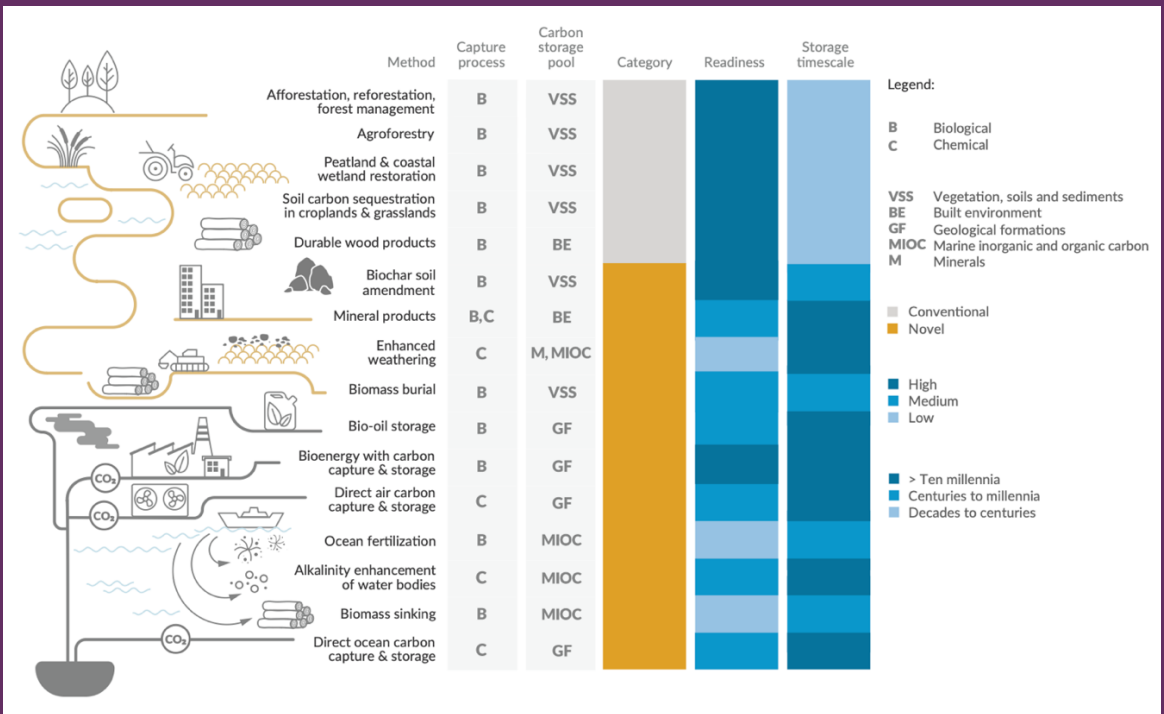
3. **Resources that limit CDR deployment** compares the resource demand of CDR with the availability of resources in the Netherlands and also considers the risks of indirect impacts and competing demand with other mitigation activities.
4. **Monitoring** evaluates what technological methods are currently available to track stored carbon and address risks and side-effects.
5. **Key Ethical Concerns for CDR** provides an overview of the key concepts for ethical CDR deployment, including climate justice, mitigation deterrence, and procedural justice.
6. **Existing governance structures and mitigation deterrence** highlights that CDR governance doesn't exist in a vacuum but embedded in system of actors and policies that need to be coherent, open, and transparent.
7. **Public acceptance and perceptions** considers the importance of understanding how CDR is perceived and evaluated by citizens and discusses social engagement necessary for procedural justice and for societal success of the implementation of CDR projects.
8. **Stakeholder Perceptions on CDR in the Netherlands** provides an overview of viewpoints from nine stakeholder interviews conducted in the process of this report. Feedback from these stakeholders, as well as the workshop, and written input, were incorporated throughout the report.
9. **Research needs and recommendations** provides a summary of research gaps and key recommendations for the governance of CDR and CDR research in the Netherlands.

What is CDR?

The defining feature of a CDR system is that it **uptakes** and **stores** atmospheric CO_2, whether via natural processes (e.g., uptake via photosynthesis, storage in ecosystems) or technological ones (e.g., uptake via chemical solvents, storage in geologic formations). Systems that only capture and store fossil CO_2 (e.g., CO_2 captured from fossil fuel combustion or cement production) reduce the amount of CO_2 added to the atmosphere, but are not CDR.

Each combination of uptake mechanism and storage medium represents a different type of CDR (see figure below), each with different considerations for resource use, efficiency, risks, uncertainties, co-benefits, and trade-offs, which in turn affect potential scalability. They also vary widely in their level of technological development, though no CDR technology has been deployed at large scale for the deliberate purpose of reducing atmospheric CO_2.

CDR also has impacts beyond atmospheric GHGs, which vary both with CDR type and implementation specifics. CDR systems are resource intensive, starting with carbon and energy, and may also require large quantities of land, minerals, water, or other resources. This can lead not only to competition for resources, but potentially other impacts to ecosystems and human health from the CDR activities, their supply chains, and their wastes.



Overview of CDR technologies. Figure from Edwards et al., (2026, CC-BY). Detailed characteristics and trade-offs of specific CDR systems are discussed in the following chapter.

Uptake of atmospheric CO_2

The process by which CO_2 is extracted from the atmosphere is typically the most energy-intensive component of a CDR system, as it requires separating and concentrating an extremely diffuse substance (CO_2 accounts for <0.05% of air by volume). However, the type of resources required to supply that energy varies with the uptake mechanism. Even assuming access to abundant resources, the rate of CO_2 uptake also varies between uptake pathways. For example, different types of biomass have different average annual growth rates, and while the rate of weathering and carbonation of minerals are both determined by exposed surface area—weathering is a destructive process, so exposed surface area and thus CO_2 uptake speed increases over time, while in carbonation bound CO_2 decreases exposed surface area, thus slowing uptake over time.

Pathways of CO_2 uptake

Uptake pathway	Factors affecting rate of uptake	Key resources
Photosynthesis *CO_2 in air → biomass*	Stable availability of sunlight, water, heat—too much or too little can hinder photosynthesis. Availability of other nutrients (e.g., nitrogen, phosphate). Different forms of biomass also have different growth rates, and growth rate varies over a plant's lifetime	**Land**, thus providing access to sunlight **Water**, e.g., rainfall or irrigation **Nutrients**, e.g., in soil or added via organic or artificial fertilizer
Mineral weathering *CO_2 in air → dissolved bicarbonate*	Exposed surface area of mineral Ambient temperature and humidity—weathering rates increase with higher temperatures and more water	**Reactive minerals**, e.g., calcium- or magnesium-rich carbonate or silicate rocks **Electricity**, milling the rock to increase their surface area, which increases the reaction rate **Transport** of bulk minerals **Land,** to expose minerals to air
[Re]carbonation[1] *CO_2 in air → carbonate mineral*		
Chemical absorption *CO_2 in air → CO_2 bound in solvent/sorbent → gaseous CO_2*	Surface area of sorbent/solvent exposed to air Airflow rate Local climatic ambient conditions, such as humidity and temperature	**Electricity**, to power fans to move air over solvent/sorbent **Energy;** either thermal or electric, to release CO_2 from the solvent/sorbent **Solvent** (chemical) or **sorbent** (material)
Air-sea flux *CO_2 in air → dissolved bicarbonate in ocean*	Difference in atmospheric and sea surface CO_2 concentrations and seawater vertical mixing rates Water temperature (cold water holds more CO_2. Also affects abundance of phytoplankton that convert ocean CO_2 into biomass) Wind speed	**Various**, diverse CDR technologies propose to extract CO_2 from seawater, e.g., via electrochemistry or aquatic biomass photosynthesis, thus allowing the ocean to take up more CO_2, which vary in their resource demands

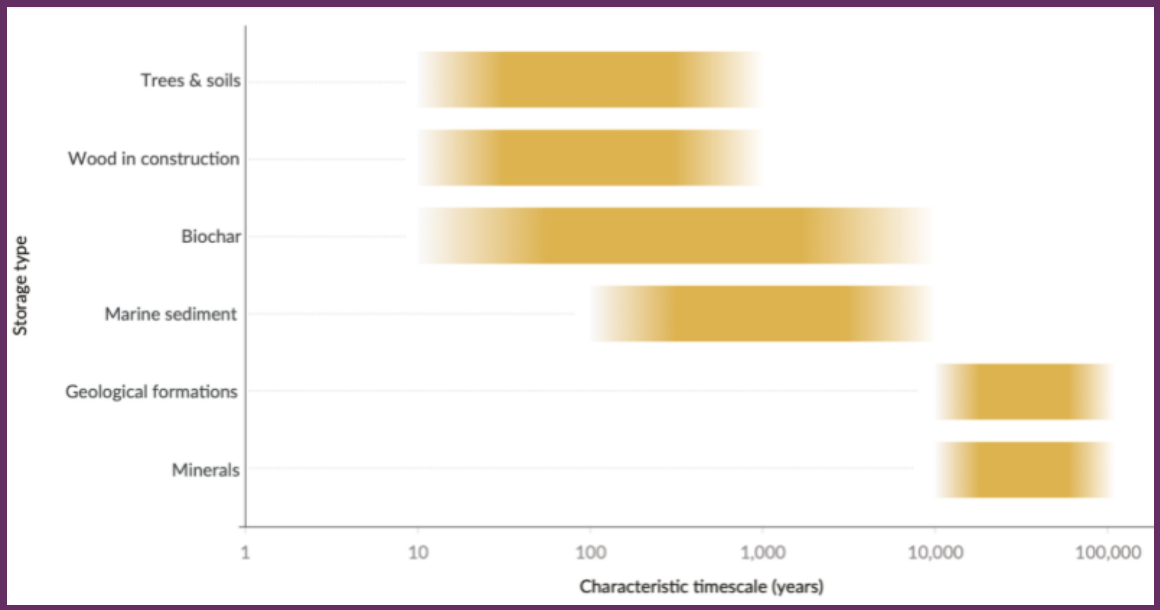
1: Recarbonation, such as occurs in concrete, requires that CO_2 is first released from a carbonate mineral, e.g., via the calcination of limestone in a cement kiln ($CaCO_3$ + heat → CaO + CO_2. Therefore, recarbonation of conventionally produced concrete is not CDR, since it does not result in a net removal of carbon from the atmosphere.

Durable storage of atmospheric carbon

Carbon dioxide removal requires both an **atmospheric source** of carbon and a **terrestrial sink** in which that atmospheric carbon is stored. That is, CDR takes CO_2 out of the atmosphere and locks it away somewhere on earth where it will not re-enter the atmosphere. The CO_2 may be stored as gaseous CO_2, such as in geologic reservoirs, or may be bound or converted into other molecules, such as biomass or bicarbonate. There are several different sinks in which we can store atmospheric CO_2, each with different considerations for durability, reversal risk, and storage capacity.

Durability—how long is the carbon stored for?

Where and in what form the atmospheric carbon is stored is the main determinant of the expected durability of a CDR activity. Expected durability, how long the atmospheric carbon is expected to stay out of the atmosphere if it remains undisturbed, is a function of many factors, including whether the form the carbon is stored decays over time (e.g., living biomass) and how the carbon reacts with its environment (e.g., biochar lifetime depends on soil temperature; gaseous/supercritical CO_2 dissolved in water in geologic formation can mineralise into rocks).



Indicative durability timescales of CO_2 storage sinks, from Lamb et al. (2023, CC-BY). These timescales assume that storage sites are well-selected and well-maintained and not subject to any disturbance that would cause the stored carbon to be re-released.

There is currently no agreement on what constitutes an "acceptable" level of expected durability for a CDR system. From a scientific perspective, any future- re-release of stored carbon results in renewed global warming and thus will have to be re-removed (using additional resources) to maintain the climate benefit of CDR. However, some argue that CDR with storage time-horizons on the order of several decades to a few centuries can provide near-term respite from warming while mitigation efforts are on-going. This argument

assumes that future generations may be more able to manage re-release emissions once societal emissions are at a residual level—an assumption that may or may not align with future societal developments and raises questions of intergenerational justice. The issue of "acceptable" durability is a key concern if CDR is used to offset emissions: different greenhouse gases have different warming effects over time, which matters if we want to keep total warming in our century below a set threshold (e.g., 1.5°C by 2100). Therefore, from a scientific perspective, it is critical to ensure that the warming and cooling effects of emissions and the removals that offset them are equal and opposite, not just in total magnitude but also in timing.

Reversal risk—what can cause the stored carbon to be unexpectedly released into the atmosphere?

If left undisturbed, minerals stay chemically stable; trees grow and die and regrow; gas stays trapped underground; biochar decays over time. However, external factors, such as droughts, pests, or deforestation for ecosystems; earthquakes for geologic formations, or soil temperature change for biochar, can lead to a release of the stored carbon. This is known as the reversal risk and is specific not only to the type of CDR activity, but to the characteristics of the specific site of CDR storage. Therefore, early identification and ongoing monitoring of risks, as well as active management for reversal prevention—particularly for carbon stored in living ecosystems—is a critical component of responsible CDR deployment.

Sink saturation—how much carbon can we put where?

Finally, even if carbon is securely stored and duly monitored, there are limits to how much carbon we can put in a given sink. Once a forest is mature, it no longer takes up significant additional carbon but still needs to be managed. Only so much crushed mineral or biochar can be spread on soil without creating negative impacts for crop growth. Only so much CO_2 will physically fit in a certain geologic aquifer. Therefore, when assessing CDR deployment potentials, it is critical to assess not only annual rates of removal, but the cumulative total removal possible in the geographic area.

"Net removals"—quantifying CDR

All CDR systems require inputs of energy, materials, and services, which in turn require energy, materials, and services to provide. These inputs and their supply chains are responsible for emissions of greenhouse gases, as well as other environmental impacts, and therefore must be considered when assessing the climate benefit of a CDR system. The process of quantifying the flows of greenhouse gases in a particular system is called "greenhouse gas accounting" or "carbon accounting". This process is typically accomplished via a combination of measurement and estimation, typically following specific rules set down in a given accounting system. GHG accounting allows actors, such as corporations and governments, to track emissions in a standardized way, assign accountability, see trends over time, and impacts of decisions and changes.

Conceptual equation for calculating net removals

Net removals	=	Atmospheric CO_2 extracted and durably stored	–	GHGs emitted during the processes of CO_2 uptake, transformation, transport, storage, and in the supply chains of all processes

In GHG accounting for CDR, we estimate a CDR system's **net removals**, also called "negative emissions" or "net CDR" —the quantified life-cycle emission balance of a CDR system. Net removals refer to the quantity of atmospheric CO_2 that is durably stored minus the sum of all greenhouse gas emissions that occur during the processes of CO_2 uptake, transformation, transport, storage, and maintenance, and in the supply chains of those processes.

As decreasing levels of atmospheric GHGs is the goal of CDR, it is imperative that accounting for net removals of a CDR system must include not only the amount of CO_2 removed, but also all emissions that result from the uptake and storage processes and their supply chains (Tanzer & Ramirez, 2019). This includes material and energy inputs; emissions from land disturbance and infrastructure construction; transport and transformation of carbon; as well as monitoring and maintenance of stored carbon. In the supply chains, we care not only for the emissions from producing inputs, but also of their supply chains of energy, material, and transport inputs, all the way to extraction of resources, such as ores, biomass, and fossil fuels, and treatment of wastes. This is known as "cradle-to-grave" accounting (which estimates the associated GHG emissions over the entire process or product lifetime, from production to use and disposal, and all associated supply chains) and is typically accomplished by a process called **life cycle assessment**. Failure to fully account for the supply chain impacts of CDR can lead to the situation where CDR activities result in "net removals" on paper, but, due to unaccounted for emissions, do not actually lead to a decrease in atmospheric GHG stocks (Tanzer & Ramirez, 2019).

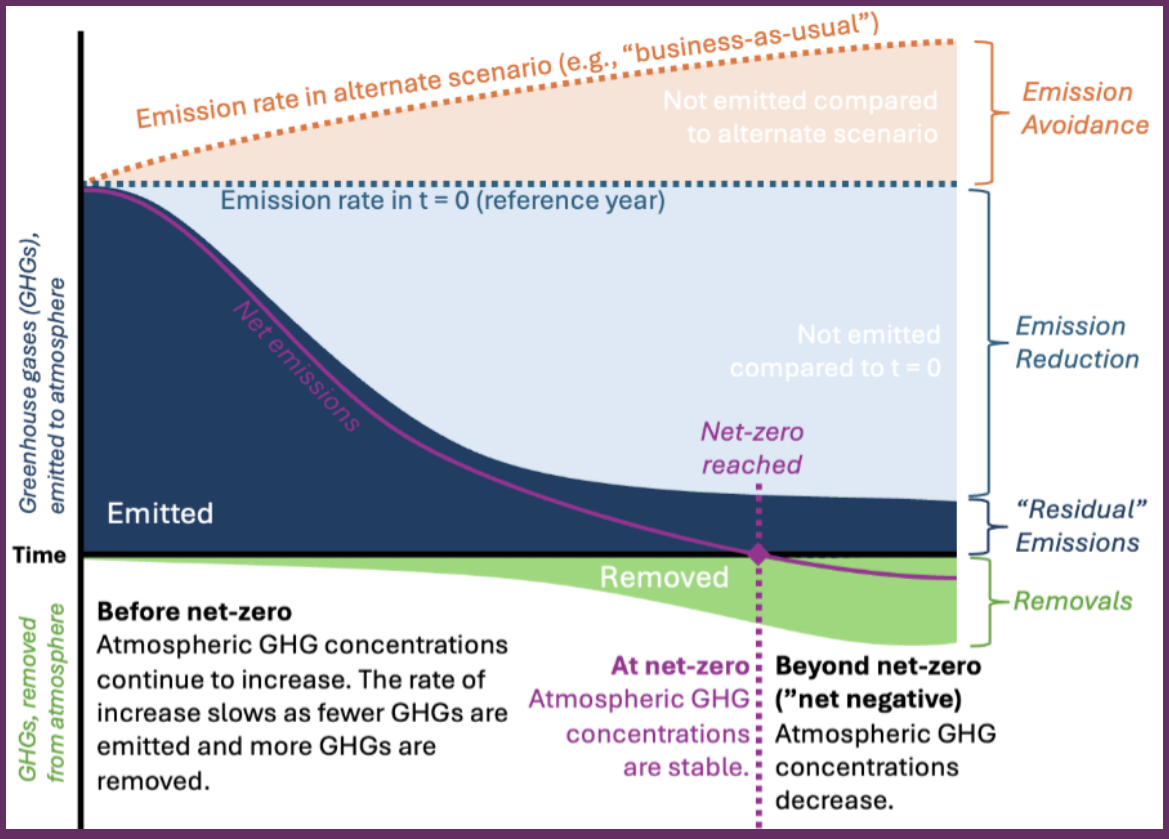
Box 1—What is global warming potential?

Net removals are typically expressed in "tonnes of CO_2 equivalent" using the IPCC accounting convention of 100-year **global warming potential** (GWP_{100}). GWP_{100} expresses how much radiative forcing can be expected from a given GHG over a 100-year period compared to CO_2, with the assumption that radiative forcing is a roughly linear proxy for warming. For example, over a 100-year period, a kilogram methane results in 29.7 times the amount of radiative forcing as a kilogram of CO_2 and therefore has a GWP_{100} factor of 29.7. This allows the effects of different GHGS to be added together.

However, GWP is an indirect metric that both flattens the impact of a greenhouse gas by integrating radiative forcing over a century and cuts off all impacts that occur beyond the time horizon (i.e., 100 years for GWP_{100}). As different GHGs vary in their radiative forcing over time, the GWP factor varies with time horizon. For example, methane is a potent but short-lived GHG, and its GWP over a 20-year time horizon (GWP_{20}) is 81.2 and 7.95 over a 500-year time-horizon (GWP_{500}). This means that GWP cannot be used to accurately assess *when* or for how long warming impacts will occur from a given set of emissions. Therefore, net-zero CO_2eq emissions does not mean net-zero warming. Also, in cases where there is a delay between CO_2 uptake and final storage, such as in a biochar system that relies on waste wood, or deployment and uptake, such as with enhanced weathering, the GWP of the CDR system will not accurately reflect when its climate benefits impacts occur. The problematic nature of GWP has been discussed since its inception but it has nonetheless become the standard convention for GHG accounting, likely due to its ease of use. But in any applications where timing of climate impacts or benefits is of concern, GWP alone is insufficient and time-explicit modelling of the radiative forcing of the respective greenhouse gas must be considered.

The Role of CDR in climate change mitigation

The role of CDR in climate change mitigation can only be seen in its relation to other mitigation actions—effective climate action requires that we stop increasing how much we emit every year and rapidly and drastically reduce how much we emit. These emission **avoidances** and **reductions**, respectively, are the overwhelming majority of mitigation work to be done, and to which well-executed CDR could play a complementary role.



CDR in its mitigation context. The pathway to net-zero emissions is defined chiefly by aggressively reducing the rate of greenhouse gas emissions (emission reduction) supported by choices that prevent increases in emission rates (emission avoidance) and activities that extract and store CO_2 from the atmosphere (removals). Net-zero is reached when the rate of removal equals the rate of emissions; if removals exceed those so-called "residual" emissions (in a post net-zero "net-negative" situation), CDR can lead to a decrease in total atmospheric GHG concentrations. Figure based on Figure 2 in Cross-Chapter Box 8, Chapter 12, IPCC (2023).

Removals have the potential to complement reductions in shrinking the amount of CO_2 added to the atmosphere year-on-year[3]. However, if CDR is used to offset emissions rather than to complement reductions, this speeding benefit is negated, as the net result of the

[3] Emission reductions and CDR are synergistic activities. Improved efficiencies and defossilisation in the energy, manufacturing and transport sectors lead to decreased net emissions from CDR supply chains, thus increasing their net removal potential. Aggressive emission reduction also reduces the demand for CDR, thus increasing the probability that it can be matched by CDR supply.

CDR and the emissions it is offsetting are, at best, cancelled[4]. Eventually, in theory, decreasing emissions will equal increasing CDR to the point where deployed CDR will be sufficient to balance the few residual greenhouse gases we emit to the atmosphere—a state described as "**net zero** emissions", though the magnitude of residual emissions and what sectors they will be from remains debated. Afterwards, further CDR deployment can remove historical emissions from the atmosphere, remediating past damage, a state called "**net-negative** emissions".

[4] Today, offsetting is the primary use case for CDR, as it is financed almost entirely through the "voluntary carbon market", which allows organisations to purchase CDR credits to use to appear to counterbalance their emissions in various public-facing emission accounts and marketing material. However, the quality and credibility of the CDR projects credited vary wildly.

Types of CDR

This chapter provides a non-exhaustive overview of many types of CDR and addresses their potential risks, trade-offs, and co-benefits. The types of CDR are grouped in line with the IPCC classification, which focuses on the method of CO_2 uptake: land-based biological; ocean-based biological; geochemical; and chemical. The subsequent chapters address constraints on key resources, and the issue of monitoring removals. While some forms of CDR (e.g., afforestation, biochar) involve mature commercial activities, it is must be emphasized that no large-scale implementation of CDR exists

Land-based biological CDR

Land-based biological CDR depends on natural, living systems capable of storing carbon in the form of biomass and organic matter. Vegetation and cyanobacteria take up carbon dioxide and produce organic carbon via photosynthesis. As the amount of biomass in a newly generated ecosystem increases, the CO_2 uptake of the system increases and then saturates. The rate at which this occurs depends on both the type of ecosystem and the local environmental conditions.

The CO_2 can then be stored in the living ecosystem or harvested and stored elsewhere. In an ecosystem, such as a forest or peatland, carbon stocks can be divided into soil organic carbon, below ground biomass (e.g., roots) and above ground biomass (e.g., stems, leaves). Protecting carbon stocks in ecosystems from reversal risks such as drought, disease, and erosion, requires continual upkeep, even after its CO_2 uptake rate slows or stops.

In other CDR activities, e.g., bioCCS and biochar, the biomass is then harvested and stored elsewhere. This leads to carbon stock loss via land disturbance but allows for the biomass to be valorised as a material or energy carrier, for the biomass to be transferred to a storage medium that is less affected by natural hazards, and/or for land to be used to grow additional biomass after an initial sink saturation is reached.

Afforestation, reforestation, and improved forest management

Afforestation is the act of planting and maintaining trees to cultivate forests on land that was either not forested before or, in cases of **reforestation**, in areas where forests were previously lost or destroyed. **Improved forest management (IFM)**, in contrast, focuses on increasing the carbon stocks of existing forests. In these methods, nature's potential for storing carbon via photosynthesis using solar energy, water and atmospheric CO_2 is used. Growth rates and carbon stock (per hectare) vary with vegetation and location.

In afforestation, the change in land-use can result in an increase of the carbon stock, especially when starting with unused, degraded land. However, the net carbon removal does depend on its land use prior to forestation. For instance, when converting peatland or grasslands into forests, even a net loss of carbon stock, and thus net emissions, rather than removals, may occur, at least temporarily (IPCC, 2019). Also, the age of a forest matters:

younger forests have a higher rate of carbon uptake, but often a lower stock of carbon. Ongoing careful forestry management and monitoring is therefore required, both to track carbon uptake and protect carbon stock against reversal risks such as drought, pests, fire, and disease. Climate change affects the capacity of ecosystems to store carbon, such as by increasing reversal risks, including large scale forest fires, via more frequent occurrence of dry periods.

At the same time, forest-based CDR can support multiple ecosystem services and co-benefits, contributing to broader sustainability goals when appropriately implemented. This includes enhanced biodiversity, improved soil quality and nutrients, and contributions to water regulation and climate adaptation (Honegger et al., 2021), though there may be trade-offs between carbon storage and other co-benefits—the healthiest forest may not be the one that stores the most carbon. In the Netherlands, species selection is particularly important given shallow groundwater tables, widespread peat soils, changing climatic conditions, and strong land-use competition (Pretzsch, 2009).

Afforestation, reforestation, and IFM are constrained by the availability of suitable land or existing forests. Afforestation and reforestation require areas that are not already high in carbon stocks or ecological value—thus excluding existing forests, peatlands, wetlands, and protected areas—while climatic conditions, soil properties, and appropriate species selection determine the long-term carbon sequestration potential. Indeed, afforestation and reforestation in inappropriate areas (e.g., peatlands, or other high-carbon ecosystems) can result in net carbon loss and biodiversity decline (Griscom et al.. 2017). It can also alter hydrological regimes through increased evapotranspiration and reduced water availability.

In the Netherlands, opportunities for large-scale afforestation are limited by high population density and competing land uses, making afforestation on marginal lands and agroforestry more likely options. Trade-offs and competition between land uses is substantially smaller in IFM because existing forests remain forests. However, trade-offs remain where management needs to balance between maximizing carbon sequestration, maintaining biodiversity, and sustaining timber production. In the Netherlands, where approximately half of the land area is used for agricultural production, even modest land-use changes could result in substantial impacts on domestic food security and export of agricultural products. Successful efforts necessitate spatially explicit planning that integrates carbon stocks, land-use demands, ecological value, and water constraints to identify suitable and sustainable intervention areas.

Peatlands restoration

Peatlands and wetlands are semi-aquatic natural areas where the ground is flooded or saturated with water, either permanently or temporarily. These systems play a key role in organic carbon burial, biodiversity and water retention. Even though wetlands (including peatlands, salt marshes, and seagrass meadows) cover 1% of the total global surface, they store 20% of ecosystem organic carbon. In wetlands, soil organic carbon is by far the biggest carbon pool, with generally between 70-95% of the carbon in wetlands stored in the soil.

Peatlands are waterlogged wetlands ecosystems in which partially decomposed vegetation forms peat layers, organic carbon-rich soil, over millennia. Whereas under natural stable conditions these systems primarily function as carbon sink, peatlands can be major sources of greenhouse gases (carbon dioxide, methane, and nitrous oxide) when disturbed and degraded. Restoring peatlands can reduce these emissions and, over time, generating removals by storing carbon in the soil. Peatland restoration also increases biodiversity (Bonn et al., 2016), improves water management, and reduces land subsidence (van Asselen et al., 2018). Potential adverse effects are higher methane emissions and land use competition with other applications. Further limiting constraints are the application of appropriate water management practices.

In the Netherlands, degraded peatlands are currently responsible for 4.2-7 Mt of CO_2 emissions per year, 2-3% of total Dutch greenhouse gas emissions (Raad voor de leefomgeving en infrastrucuur,2020). Research programs such as NOBV and NL2120 are already employed to tackle both the GHG emissions from Dutch peatlands. NOBV has the goal to achieve 1 Mt CO_2 reduction per year by 2030, whereas in NL2120, paludiculture (wetland agriculture such as reed, cattail and cranberry), is being investigated as an alternative to conventional agricultural practices.

Given that large areas of drained peatlands in the Netherlands are currently used for agriculture, the challenge of large-scale restoration lies in identifying restoration and management pathways that reduce emissions and store carbon while maintaining viable agricultural livelihoods and sustainable water management, particularly as restoration may conflict with existing drainage infrastructure. Finally, as noted, it is important to account for potential increased methane (CH_4) emissions, the influence of which varies over the time scale considered, to ensure net removals (Günther et al. 2020).

Agricultural soil carbon storage

Several techniques have been proposed to increase organic soil carbon stored in agricultural land, such as by changes in management practises (e.g., planting cover crops, conservation tillage) or by organic amendments (e.g., biochar, which is addressed later in this document). Activities to increase agricultural soil carbon storage is also known as **carbon farming**.

In contrast to afforestation or reforestation, soil carbon storage takes place on existing agricultural land, resulting in low direct competition for land. The spatial constraints are therefore based on the properties of existing land use, rather than the need for land transformation, as for afforestation. Constraints are mainly based on soil properties (e.g., texture, initial carbon content), climate (e.g., temperature, moisture) and current management practices. These affect both the potential rate of soil carbon accumulation and the total carbon that can be stored on a given plot of land (Xu et al., 2020). In particular, soil properties are characterized by high spatial variability. The potential for increased soil carbon storage in the Netherlands is closely related to the intensively managed agricultural systems (e.g., croplands, grasslands), where constraints are particularly related to high groundwater levels and large areas of peat soils. Therefore, geospatial analysis is required to identify soil carbon baselines, appropriate management interventions (e.g., reduced

tillage) and suitable areas, particularly degraded and carbon-depleted soils, which have the greatest potential for additional carbon storage.

Changes in management practices (e.g., reduced tillage, cover crops) to promote additional soil carbon storage may increase or decrease crop yield and input requirements. Ultimately, this affects the farm economics—positively or negatively—depending on the specifics of the starting situation and CDR implementation. Further, there are also trade-offs between carbon storage and other environmental objectives (e.g., nitrogen emissions, water quality, soil compaction) (Xia et al. 2018). This is particularly relevant for the Netherlands where agricultural production is highly optimized and already creates environmental pressures (e.g., nitrogen emissions) in extensive areas. It is also important to note that the durability and net removal of soil carbon is highly uncertain because further changes in soil management can result in carbon emissions. Like all ecosystem-based CDR, protecting soil carbon stocks, once established, requires continued upkeep.

Biomass with carbon capture and storage (BioCCS/BECCS)

BioCCS is the application of carbon capture and storage (CCS) technology to biogenic CO_2 streams. When the CO_2 captured and stored originates from the combustion of biomass for energy, the system is typically called **BECCS**—bioenergy with CCS. In a bioCCS system, the CO_2 in exhaust gases from the combustion, fermentation, or other chemical conversion of biomass is captured, purified, transported, and injected into a geological formation. BioCCS can refer both to new facilities constructed for dedicated bioCCS or the application of CCS to existing streams of biogenic CO_2, such as in waste-to-energy plants, paper mills, ethanol and biogas production facilities, and biobased CHP plants. Currently, there are three bioCCS plants operating globally, all capturing emissions from biomass fermentation (e.g., ethanol), all located in the US, with a total capture capacity 1.4 Mt/year of biogenic CO_2 stored in saline aquifers (Global CCS Institute, 2025)[5].

BioCCS is potentially one of the most complex CDR techniques because it involves the integration of supply chains from biomass production, conversion, transport as well as CO_2 capture, transport, and storage. By themselves, industrial biomass use, CO_2 capture and compression, pipeline gas transport, and geologic CO_2 injection are all commercialized technologies. However, costs remain high due to the need for individual customisation of CO_2 capture facilities and the upfront investment required for CO_2 transport and storage infrastructure and CCS has a track record to not reach final investment decisions (Kazlou et al., 2024). Moreover, the durability, monitorability, and reliability of geologic storage are theoretically very high but is still subject to many uncertainties, which are discussed in the next chapter.

[5] Two plants, with a capture capacity of 0.6 Mt, were excluded as their CO_2 is used for enhanced oil recovery, which is not here considered a CDR activity.

Further, if bioCCS uses dedicated energy crops, it requires substantial areas of land for biomass production. This could directly compete with food production and biodiversity conservation (similar to risks of poorly-managed afforestation), as well as impact albedo and increased nutrient (removal) and water demand (Smith et al. 2016). As large-scale additional cultivation of biomass is unlikely in the Netherlands due to land constraints, large-scale bioCCS implementation would require imported biomass, which risks the transference of negative impacts to other regions and populations. This raises questions of interregional resource appropriation and governance, as well as requires rigorous attention to accurately account for emissions in the biomass supply chain, including production, transport, and land use change.

To reduce such risks from biomass use, bioCCS could rely on waste biomass streams, such as residues from agriculture and forestry, though this then limits the supply of available biomass. More simply, CCS could be added to existing point-sources of biogenic CO_2, such as paper mills, biofuel production facilities, or waste-to-energy plants. In this scenario, the additional resource demand of bioCCS is limited to that of the capture, transport, and storage of CO_2. A 2025 study estimates that the Netherlands currently emits 1 Mt/year of biogenic CO_2 at existing point-source facilities, excluding waste-to-energy (Christianides et al., 2025). The AEB waste-to-energy plant in Amsterdam alone emits 0.6 Mt of biogenic CO_2 (Marks et al., 2022).

Due to the delay between CO_2 uptake and storage in bioCCS, the many different types and origins of biomass, and the variety of system configurations and scale, and the risk of indirect impacts from land-use change and competition, it is challenging to estimate the net climate impacts of bioCCS. Estimates may also be very sensitive to modelling assumptions, such as on what geographic or temporal scale CO_2 uptake is considered. Further research is needed not only to understand the environmental and social impacts of different bioCCS system configurations, but also the accounting models and metrics need to evolve to transparently estimate distribution of impacts over time and space.

Biochar

Biochar is a stabilised biomass product produced via pyrolysis—thermal decomposition in an oxygen-free environment—in essence, charcoal. Depending on configuration, pyrolysis results in biochar yields of 10-60% of input carbon (Mašek et al., 2013), with the remaining carbon converted into bio-oil and biogas, which can be used to provide energy for the pyrolysis process. Most commonly, biochar is proposed to be spread over soils, though it could also be stored in bulk or in construction materials, such as concrete. Net removals from biochar are dependent on the chemical properties of the specific biochar; the efficiency of the biochar production process; the characteristics of the storage site; and, if stored in soils, soil-biochar-microbiome interactions. A fraction of the carbon in biochar is anticipated to be highly stable, with an expected storage duration of multiple centuries, while the remaining carbon content is volatile and will decay over time (Woolf, 2021). The fraction of stable carbon is dependent on the type of biomass and production conditions, while the decay rate depends on the conditions of the storage site.

Biochar is commercially produced, though only recently specifically for CDR purposes (Lamb et al, 2023). It is used as a soil amendment due to benefits such as water retention, decreases in nitrogen emissions, and yield improvements (Tisserant et al, 2022; Antonangelo et al, 2025). However, the magnitude of these benefits is highly specific to the type of biochar and the application site. Biochar also has risks of negative impacts, particularly at high application rates, such as reductions in yields, increases in soil GHG emissions, and increased plant uptake of heavy metals (Antonangelo et al., 2025).

Biochar, like bioCCS, relies on harvested biomass, so the impacts on land use depend on the type of biomass used. The use of dedicated grown biomass would compete with existing land use and agricultural production. If biochar production uses existing biomass residues, direct land use competition is relatively low compared to other land-based CDR techniques like afforestation and reforestation. Spatial requirements, therefore, rather relate to the distribution of existing biomass resources (e.g., crop residues, forestry by-products) and the proximity of processing infrastructure and application sites. However, the availability of biomass residues is limited and subject to competition from other applications, such as energy production and animal feed or even bioCCS, which is highly relevant in intensive agricultural systems like in the Netherlands where the surplus of available biomass is generally low. In addition, the use of agricultural or forestry residues that would otherwise be left on the land needs to be critically assessed against sustainability constraints, as removing these residues for use elsewhere could affect soil health, biodiversity and other carbon stocks (e.g., soil carbon) (Searchinger et al., 2018).

From a deployment perspective, the scalability of biochar depends on (a) the availability of suitable biomass, (b) the infrastructure to transport, store, and pyrolyse the biomass, and (c) availability of land on which to apply safely the biomass. In the Netherlands, agricultural soils suitable for biochar application are assumed to be abundant, but specific evaluation is needed to understand soil-biochar interactions and feasible application rates. The availability of sustainable biomass could be more limiting due to competing demands such as animal feed, bioenergy, and bio-based materials. Managing methane emissions during biochar production is another key technological challenge, particularly for small-scale or distributed biochar production.

Besides the key uncertainty of competition for biomass resources, quantifying net removals of biochar presents a different challenge, as the fraction of stable biochar is a function of the original biomass composition as well as the reaction condition of pyrolysis and the decay rate of biochar in soil depends on soil temperature, soil type, and other environmental conditions (Woolf, 2021), which are made further uncertain by changing climate and weather patterns. Like bioCCS, temporally and geographically explicit modelling of social and environmental impacts of biochar are critical.

Further, the origin of biomass used, the conversion efficiency of production, and any losses from the co-production of methane, are highly relevant for assessing net removals in biochar-based CDR. Greenhouse gas emission from the full supply chain (e.g., biomass production, transport and processing as well as pyrolysis biochar transport, application) need to be taken into account to quantify net removal.

Ocean-based biological CDR

Several forms of proposed CDR rely on removing CO_2 not directly from the atmosphere, but from the ocean, which is the largest terrestrial reservoir of CO_2. Reducing the concentration of CO_2 in ocean surface water corresponding increases the air-sea CO_2 flux—thus that by removing CO_2 from the ocean, the ocean will then remove more CO_2 from the atmosphere. Proposed ocean CDR (also known as marine CDR, or mCDR) pathways vary in the mechanism of ocean CO_2 uptake (biological or (geo)chemical) and also whether the removed CO_2 is then stored in or out of the ocean. Monitorability, understanding of co-impacts, and governance are key challenges for ocean CDR, though vary by approach, and are due in part to the difficulties of tracking impacts and assigning liability for interventions in a vast open system.

Ocean fertilisation

Ocean fertilisation seeks to increase stocks of phytoplankton—which uptake ocean CO_2 via photosynthesis—by fertilising the ocean with nutrients, most commonly, iron. This phytoplankton then enters the marine food web when it is eaten by larger creatures. It is theorised that eventually a fraction of this carbon will eventually end up in marine sediment through the death and decay of final predators as well as uneaten phytoplankton. However, ocean fertilisation requires adding large quantities of material to the ocean and is currently explicitly prohibited by the London Protocol[6] (Silverman-Roati & Webb, 2026).

The net removal potential of ocean fertilisation is poorly understood both due to the challenges in predicting phytoplankton response to ocean fertilisation and to monitoring the resulting food web interactions. Further, accounting for impacts in the supply chain of producing and distributing the fertilising nutrients is also required.

Macroalgae cultivation and sinking

Like ocean fertilisation, **macroalgae sinking** focuses on the stimulation of marine biomass production that is then intended to be stored in the marine food web and seabed sediments. Unlike ocean fertilisation, it stimulates the growth of larger marine seaweeds, such as kelp. The seaweed is farmed in coastal or open waters, harvested, and then sunk. This is presumed to store the seaweed's carbon in deep ocean waters and sediment, thus preventing it from being rereleased into surface waters or the atmosphere.

The impact of large-scale seaweed cultivation and sinking on marine ecosystems and ocean chemistry is unknown. Like all forms of ocean CDR, understanding the interactions of the intervention on the marine environment is critical for assessing both net removal potential and potential positive and negative co-impacts, but is also exceedingly challenging due to

[6] London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (1972) and its implementing protocol (the London Protocol, 1996), which expressly includes "marine geoengineering", explicitly including ocean fertilisation, and for which OAE is being considered.

the complex and changeable nature of the ocean environment. In one recent experiment (Bauer et al, 2026), over 90% of sunk kelp was subject to predation within 100 days, highlighting both that expectations for sediment storage may be overoptimistic and that macroalgae sinking has direct impacts on deep sea biomes.

Marine bioCCS and marine biochar

Cultivated marine biomass can also be removed from the ocean and used as inputs into bioCCS and biochar processes, described above. This can increase both the stability and monitorability of the stored carbon, thus potentially easing the estimation of net removals. However, this also leads to a net extraction of nutrients from the ocean environment. Processing of marine biomass, with its high water and salt contents, also creates a technical challenge for bioCCS and biochar processes that can lead to high energy demand or decreased yields.

Coastal revegetation and restoration

Coastal revegetation and restoration (also called "blue carbon") can be considered a semi-ocean, semi-terrestrial form of CDR. Like terrestrial wetland ecosystem restoration, coast revegetation has the potential to improve biodiversity and provide water management co-benefits but come with several challenges. Mangrove forests—the most effective carbon-sequestering wetland—have declined due to deforestation, both globally as well as in the Dutch Antilles, resulting in the release of stored carbon. Restoring these systems and additional coastal revegetation can be attractive measures to capture carbon as well as increase other ecosystem services (Mcleod et al., 2011).

In Europe and the Netherlands coastal revegetation and restoration is being studied extensively for enhancing biodiversity, coastal protection, water retention and resilient infrastructure. Carbon sequestration in these systems is also receiving more attention recently. The EU granted Horizon Europe projects (REST-COAST, Rewet, ALFAwetlands, Wet Horzions) where carbon sequestration is part of the broader scope of restoration (European Commission, 2021). Earlier research shows that deploying these "nature -based solutions" for the purpose of carbon sequestration may be overstated as methane emissions from sediment may increase, as well as the inclusion of "allochthonous" carbon (van de Broek et al.,2018). This is carbon (e.g., dead plant material) that has been sequestered outside the system's perimeter but gets buried (in sediment) inside the system.

In the Netherlands, dense use of the coastal environments and North Sea (e.g., shipping, fisheries, wind farms, protected areas) may limit the spatial availability for coastal revegetation. In addition, the Dutch Caribbean territories could offer higher potential for certain blue carbon approaches that are particularly related to the tropical environments like mangroves.

(Geo)chemical CDR

CO_2 can also be removed from the atmosphere or the ocean via non-biological chemical processes. In the case of terrestrial (geo)chemical CDR, permanent carbon dioxide removal can potentially be realised by storing physically or chemically extracted atmospheric CO_2 in geological storage locations (e.g., empty oil and gas fields), saline aquifers or by carbonation of unsaturated mineral rocks (e.g., olivine and wollastonite), thereby forming bicarbonates.

Direct air (carbon) capture and storage (DACCS)

In **direct air capture** (DAC), CO_2 (present in ambient air at a concentration of ca. 425 ppm (0.04%)) is selectively collected and concentrated in a liquid ('solvent') or on a solid ('sorbent'). That CO_2 is then released from the capture medium, which can then be reused. When combined with geologic storage of the captured CO_2, **DACCS** (DAC + CCS) can result in permanent storage of atmospheric carbon.

In DAC, atmospheric CO_2 uptake occurs via a reversible reaction between CO_2 and the sorbent / solvent. Whereas the uptake of CO_2 into the solvent/sorbent is spontaneous and mildly exothermic, the regeneration of the sorbent/solvent (to release the captured CO_2) requires significant energy input. For sorbent-based DAC, state-of-the-art processes require around 4 MWh/t CO_2, of which typically 80% is thermal energy[7] (for heating and sorbent regeneration) and 20% is electrical (especially for pumping the large amounts of air). All-electric DAC options are also under development, using electrochemical solvent (or sorbent) regeneration and via the use of heat-pumps.

DAC has four main challenges. The low concentration of CO_2 implies that typically around 2500 m^3 of air is processed per kg of CO_2. The low CO_2 concentration also requires the capture mechanism/reaction to be very selective to CO_2 and not bind to other more abundant molecules, such as water. Moreover, the CO_2 sorption process must be fast; a gas residence time of less than a half-second is typically used, to avoid excessive equipment volumes for the capture unit. Finally, current DAC technologies are sensitive to weather conditions, especially the relative humidity of the ambient air.

Due to DAC technologies' dependency on the ambient conditions, which strongly influences the energy performance of the DAC systems, it can be difficult to compare their performance. Further, whereas DAC processes with liquid solvents usually have a net water consumption, the solid sorbent DAC processes typically have a net water production. This can lead to a co-benefit depending on the scale and suitability of the produced water. In contrast, deployment of solvent-based DAC needs to be considered in the context of competing water demand (e.g., from households, industry, and data centres) and increasing strain on available water resources.

[7] The thermal energy requirement is typically required at a temperature-level of 80-150°C, with exceptions up to 900°C.

Compared to most of the other CDR techniques, DACCS is generally independent of land type restrictions. However, this technique is particularly constrained by the need for low-carbon thermal and electric energy as well as CO_2 transport and storage infrastructure (Keith et al., 2018; Fasihi et al., 2019). Therefore, while the direct land requirement of DACCS is relatively small, particularly compared to biobased techniques like afforestation, spatial optimization is still an issue for the development of infrastructure and transport of CO_2. In the Netherlands, the deployment is potentially closely related to the access to low-carbon energy (e.g., wind farms for electricity, industrial waste or geothermal heat for thermal energy), to transport infrastructure (e.g., CO_2 pipelines at port of Rotterdam), and to the depleted gas fields in the North Sea as potential storage. (CCS infrastructure is discussed further in the next chapter). Indeed, competition for new renewable energy is probably the most relevant trade-off for DACCS in the Netherlands. It is also important to note that, also due to DAC's high energy demand, DACCS could result in limited removals—or even produce net emissions—if it is powered with fossil fuels (Fasihi et al., 2019), which is a risk if the DAC process relies on grid electricity rather than dedicated renewable energy sources.

Enhanced (rock) weathering

Mineralisation and **enhanced weathering** (also called enhanced rock weathering) rely on alkaline minerals that react with CO_2, forming solid minerals into which the carbon becomes incorporated—either into the rocks themselves, in the case of mineralisation, or into dissolved bicarbonates, in the case of enhanced weathering. These processes naturally occur on timescales of thousands to millions of years. However, it can be sped up by grinding reactive minerals—such as rocks rich in magnesium oxide and ferrous oxide and low in silica, e.g., olivine, basalt, or wollastonite—into smaller pieces, thus increasing their surface area exposed to air. These minerals then react with CO_2 and water in the air, forming carbonate, which consequently can react with calcium to form magnesium carbonate, calcium carbonate, or dissolve in (ocean)water.

The net removal potential of mineralisation and enhanced weathering is dictated by several factors: the mineral dissolution rate, application rate, and method of mining and transport. The technology is relatively straightforward can be combined with other land use practises. The applications attracting most interest are agricultural applications, beach sand enrichment, and shallow sea deposition (e.g., covering undersea cables and pipelines), as water exposure increases dissolution rates (Khan, 2025; Meysman & Montserrat, 2017). The disadvantages of rock weathering are challenges in monitoring the uptake rate, which vary over time and with climatic conditions, as well as potential adverse ecological effects due to leaching of heavy metals (nickel).

Enhanced weathering can be implemented on existing agricultural land (Beerling et al., 2020), roofs, or transport infrastructure (e.g., distribution on railways), where no land conversion is required. Therefore, it has limited direct land-use competition. Rather, enhanced rock weathering is mostly constrained on spatial level by the availability of suitable rock material, infrastructure (for chemicals, grinding, and transport) and appropriate application areas. The Netherlands have limited rock resources, but the port infrastructure

of the Netherlands potentially supports the import of silicates. However, mining and transport-related emissions must be considered when quantifying net removals. Therefore, geospatial techniques are necessary to identify suitable application areas and to optimize supply chains, as the mining, grinding and transport of suitable minerals also require logistics and energy. Further, the slow weathering rates are influenced by climate conditions (e.g., temperature, moisture, soil chemistry, with warm humid conditions increasing uptake rates), as well as the exposed mineral surface area. Increasing surface area increases uptake rates but also increases energy demand of grinding and risks of health hazards from small particulate matter.

Enhanced weathering has potential co-benefits and trade-offs. If applied to agricultural soils, it could enhance soil fertility and nutrient supply, potentially resulting in improved crop productivity. However, these potential benefits are highly site-specific, depending on local soil and climate, and remain uncertain (Beerling et al., 2020; Hartmann et al., 2013; Schiedung et al., 2026). It is also possible that a fraction of the silicates will be transported by run-off to oceans, potentially resulting in higher alkalinity in the ocean and finally reduced ocean acidification (Hartmann et al., 2013). On the other hand, enhanced weathering can result also in the release of toxic trace metals (e.g., nickel), negatively affecting soil and water quality, but again this depends on the composition of the weathering mineral and the application rate. Therefore, environmental safety together with logistics are the main trade-offs (Levy et al., 2024), which would be also the case in the Netherlands. This requires the spatially explicit evaluation of environmental impacts and optimization of application strategies together with a monitoring of supply chains in order to ensure net removals and minimise the risk of negative side effects.

Ocean alkalinity enhancement

Ocean alkalinity enhancement (OAE), including "ocean liming" and "ocean weathering", relies on spreading silicate or carbonate minerals, or more reactive alkaline materials, such as lime, directly across the ocean surface. These alkaline materials then react with dissolved CO_2. While the underlying chemical reactions of OAE are well-established, further ecological interactions are not yet well-understood, which may affect the net removal potential as well as other environmental impacts. The dispersion of added materials is also difficult to track and creates challenges of how long the material stays in contact with the atmosphere—which determines how much CO_2 uptake can occur—and separating the effects of OAE from natural processes. Another important consideration is the supply chain emissions from the mining, transport, processing, and spreading of the alkaline minerals. Like with other forms of ocean-based CDR, understanding of ecosystem interactions and diffuse risks, monitorability, and liability are key governance issues to be addressed.

As OAE requires adding large quantities of material to the ocean, it is subject to international laws to prevent marine pollution, and permitting therefore requires international approval. However, these regulations explicitly allow for marine scientific research to be conducted within territorial waters. Current knowledge of OAE is based primarily on modelling and lab-scale experiments, though small-scale nearshore pilot studies (e.g., Savoie et al., 2025; Jankowska et al., 2026) have started to be conducted.

Direct ocean carbon capture with storage (DOCCS)

Direct ocean carbon capture with storage (DOCCS) typically uses electrochemical or photochemical processes to extract dissolved CO_2 directly from seawater. The dissolved CO_2—which is stored in seawater as inorganic carbon molecules—is converted into pure CO_2, which is then separated as a gas, and can be stored in geologic formations, such as with DACCS and bioCCS. The decarbonised seawater is then returned to the ocean, thus increasing the ocean's capacity to remove more CO_2 from the atmosphere. Direct ocean capture (DOC) is not currently a commercialised technology—the largest DOC plant currently in operation is a 1000 t CO_2/year pilot in Hawaii, but experimental initiatives also exist in the Netherlands (e.g., SeaO_2).

The viability of DOC is dependent on access to abundant renewable energy, which is necessary for both the DOC process itself[8], as well as for pumping, pre-treatment, and re-release of seawater. Co-locating DOC with desalination technologies has been suggested to distribute this energy use between multiple purposes, though the scale of DOC would be limited by the scale of the desalination plant (Digdaya et al., 2020). Like DACCS, the potential efficiency of DOCCS varies geographically with local (ocean) climatic conditions, and the geospatial concerns are similar, particularly regarding access to CO_2 transport and storage infrastructure and low-carbon energy, with the further complication of siting the DOC facility itself on the coast. Like all forms of ocean CDR, uncertainties remain over impacts the technology will have on the marine ecosystem when deployed at scale, such as from changes in local pH.

[8] Ca. 1.22 MWh/t CO_2 in one commonly cited study (Digdaya et al., 2020) but ranging up to 15 MWh/t CO_2 in others (Karunarathneet al, 2025).

Resources that limit CDR deployment

While CDR systems are diverse in how they uptake and store atmospheric carbon, in their technological maturity, and in their profiles of risks and uncertainties, a key determinant of scalability is whether sufficient resources are available for their deployment. While biomass and ecosystem-based CDR methods have high spatial constraints, industrial methods are bound to infrastructure and are energy-availability driven, and CDR that stores CO_2 geologically is limited by suitable subsurface storage sites.

Key limiting resources to CDR deployment[1]

CDR System	Limiters for CO_2 uptake	Limiters to CO_2 storage
Afforestation	Land (including access to sunlight, water, and nutrients)	
Coastal revegetation		
Wetlands restoration		
Peatlands		
Soil carbon storage		
BioCCS/BECCS	Harvested biomass (Land, indirectly) CO_2 capture infrastructure	CO_2 transport infrastructure Geologic storage
Biochar	Harvested biomass (Land, indirectly)	Land
DACCS	Energy CO_2 capture infrastructure	CO_2 transport infrastructure Geologic storage
Enhanced weathering	Minerals Energy	Land
Ocean alkalinity enhancement	Minerals	Uncertainty
Ocean fertilisation	Uncertainties are too high to determine limiting factors	
Macroalgae sinking		
DOCCS	Energy Coastline infrastructure	CO_2 transport infrastructure Geologic storage

1: Non-resource limiting factors are discussed in the previous chapter and in the table "Pathways of CO_2 uptake"

Land

In the Netherlands, land is a scarce resource due to the country's large agricultural sector (accounting for 53.7% of the total land area) and high population density. Grasslands for livestock grazing and animal fodder crops are the main agricultural land uses, accounting for 65% of agricultural land use. Other land uses include forests and other ecosystems, tidal water (e.g., Wadden Sea, North Sea), and waterways (e.g., rivers, lakes, canals). The table below gives an overview of the land uses in the Netherlands and the area in use (CBS, 2023).

Conversion of (arable) land to increase afforestation, coastal revegetation, wetlands restoration, peatlands restoration, and/or biomass production for biochar or bioCCS directly compete with these land uses. At the same time, a transition towards lower-emission and less intensive agricultural systems (e.g., reduced livestock production via a shift in dietary

preferences) may create opportunities for land-based CDR approaches, including afforestation, peatland restoration, and agroforestry. This creates potential synergies between reducing agricultural emissions and increasing carbon removals, although careful spatial planning is required to balance competing land-use demands. However, the net system-level effects of combining agricultural mitigation measures and CDR deployment remain uncertain, particularly with respect to food production, biodiversity, and water resources. Agricultural soil carbon storage does not directly compete with other land uses but may require less intensive agricultural practices, affecting agricultural output. Biochar and minerals for enhanced weathering can also be applied to agricultural lands, thus reducing land competition but these are also expected to have impacts on agricultural productivity, which can be beneficial or detrimental, so must be assessed on a case-by-case basis.

Land is also a limiting factor for CDR that relies on the availability of low-carbon power or transport infrastructure for CO_2 or energy. While CO_2 pipelines and electricity transmission grids do not require the quantity of land that biomass production or solar energy generation does, it may require substantial coordination if it's necessary to secure right-of-way across many landowners and/or avoid protected nature areas.

Land uses in the Netherlands as of 2017 (CBS, 2023)

Land use	Land area (ha)	Percentage of total area
Total	*4 154 302*	*100.0%*
Agriculture	2 230 445	53.7%
Woodland and nature	501 461	12.1%
Tidal water	415 211	10.0%
Inland water	374 381	9.0%
Built-up area	370 140	8.9%
Transport	115 108	2.8%
Recreation	108 335	2.6%
Other	39 221	0.9%

Harvested biomass

BioCCS and biochar require biomass as input. The origin of this biomass heavily dictates the economic viability as well as the net removal of the activity, as cultivation and transport of biomass can generate substantial emissions. In particular, transport modes and distances within the value chain can have significant impact on the net removal potential. While the use of locally produced biomass mass is preferred, increased domestic production is unlikely in the Netherlands given constrained land availability. The use of imported biomass is a possibility, but has its own set of governance challenges, such as ensuring sustainability of supply, "fair share" use of resources, and the risk of exporting impacts (e.g., on food security or biodiversity) to other regions. However, such interregional governance challenges are out of scope of this report.

Using biomass feedstock for bioCCS or biochar production that would otherwise have been used for higher value applications such as crops for food or wood

for manufactured goods is controversial. An alternative is to deploy waste biomass, such as forestry residues, mill chips, agricultural waste products, domestic green waste (e.g., garden waste, roadside grass), or post-consumer organic waste. However, as the biochemistry industry progresses to converting more complex forms of biomass, competition for even "waste" biomass is expected to increase. This is also true for biogenic CO_2 from existing sources, which can be captured for bioCCS, but in the future may be demanded for fuel and chemical synthesis. Moreover, using biomass waste as input for higher-value conversion processes, such as biogas production and compost substituting natural gas use and fossil fertilizer might be preferable to BECCS from a climate point of view. Meanwhile, long-term availability of waste biomass is uncertain, particularly in light of efforts to increase biomass use efficiency, reduce waste generation, and increase recycling.

Minerals

While minerals that can be used for enhanced weathering are abundant worldwide, there are no significant deposits in the Netherlands. Throughout Europe storage materials as olivine, basalt, and wollastonite are widely available, with olivine being particularly abundant in Norway, and could be imported but the associated emissions of such bulk mineral transport and subsequent energy use for comminution must be accounted for in quantifying net removal.

Industrial residues, such as slag from energy and steel production and demolished concrete are another source of minerals that can uptake CO_2, however their ability to do so is the result of the release of CO_2 from a more stable source mineral (e.g., limestone calcination) and while their recarbonation can result in useful emission reduction and deserves consideration, it is unlikely to result in actual net CDR, except in specific system and accounting configurations.

Energy generation and transmission

Energy, both thermal and electric, is a key requirement for engineered CDR technologies as direct air capture, direct ocean capture, enhanced weathering, and for the CO_2 liquefaction and transport necessary for the CCS part of DACCS, DOCCS, and bioCCS. For energy-reliant CDR technologies, it is particularly important that the life cycle GHG emissions of the energy source is sufficiently low, to ensure that the process results in net removals.

Demand for electricity is a key limiter in the Netherlands, where grid congestion (Partners in Energie, 2026) is already stymying industrial electrification efforts, as well as normal expansions of industry and housing stock, and is under further pressure by increasing demand from data centres. While modular renewables such as solar and wind means that additional generation capacity can be added in a period of months, increasing capacity for electricity transmission and storage via large-scale infrastructure upgrades is a time and investment-intensive process.

In theory, a highly electrified CDR system could provide offtake for temporary excesses of renewable electricity during particularly windy and/or sunny periods However, this still requires that the electricity grid has sufficient transmission capacity and that there is not already competition from other electrified processes for "excess" electricity (e.g., from electrolytic hydrogen production). This would also raise the average cost of CDR by requiring installing CDR capacity that is only used during periods of peak electricity generation and otherwise remains idle.

Heat requirements for CDR technologies (e.g., DACCS) can be fulfilled by (industrial) waste heat streams or geothermal heat. However, CDR would compete with district heating networks for the availability of this waste heat, particularly if its availability decreases due to increased efficiency and electrification. However, as demand for heating is seasonal, availability for other uses, such as CDR, may be greater in the summer months. Alternatively, if the required temperature of heat for the CDR process is not too high, heat pumps can be used to efficiently upgrade low-grade heat, but this creates further demands on the electricity system.

CO_2 transport and storage infrastructure

For CDR technologies where the CO_2 remains in gaseous form (e.g., DACCS, DOCCS, and bioCCS), infrastructure for transport and injection into a suitable geologic storage site is required. Availability of suitable storage varies regionally and may not be co-located with available biomass or low-carbon energy resources (e.g., Finland has potential for DAC using renewable electricity, but no geologic storage capacity). Across Europe, several CC(U)S clusters (hubs) are in various stages of development, coupling CO_2 sources (as industries) with CO_2 storage sites. CO_2 transport and storage availability for CDR competes with the demand for CCS from fossil-based industries sectors, such as cement and fertilizer production.

Transport of CO_2 can occur via pipeline, ship, or truck. CO_2 pipeline transport is considered to be the most efficient in terms of both of cost and energy, as it can best make use of economies of scale, but requires substantial upfront investment in capital infrastructure, typically coordinating many actors as well as long-term contracts with both CO_2 suppliers and offtakers. Having the option to transport the CO_2 per ship unlocks storage potential for CO_2 capture not located near pipeline infrastructure. However, ships must be built or refitted to transport CO_2, which is heavier than the more commonly shipped liquid natural gas. Truck or train transport of CO_2 is an option for industries not directly connected to the CO_2 pipeline systems or near waterways. However, truck transport of CO_2 increases costs and associated emissions from both transport and losses, and, depending on volume, can lead to substantial increases in road congestion.

For pipelines, the risk of leakage is low and is expected to be similar to leakage risk from transport of other gases (Schueler et al., 2026). However, the transport system must be designed for the specific properties of the CO_2 stream, which may have different risks of failure compared to natural gas (Xi et al., 2023). Further, to prevent corrosion of pipelines or

transport containers, the CO_2 must be free of contaminants, such as water, nitrogen and sulphur. For bioCCS, contaminant removal is also a key part of preparing exhaust gas for capture and increases the energy and material demand of the system.

After transport, CO_2 must be securely stored in a suitable underground formation, such as depleted gas and oil fields or saline aquifers, which must be covered by an impervious cap rock that prevents the escape of stored CO_2. Gas fields were able to hold natural gas reserves for millions of years and, therefore, are potential storage locations for CO_2 with limited expected leakage risks. However, characterising the geology of specific storage sites prior to injection and continued monitoring are critical to preventing and responding to unexpected CO_2 movement both during and after injection. Of particular concern for depleted gas and oil wells is understanding the impacts of existing boreholes in the field (Gholami et al., 2021).

The Netherlands have a significant potential CO_2 storage capacity (1260-1750 Mt in offshore depleted oil and gas fields) (TNO, 2025)[9]; equivalent to 20-40 years of the current annual national CO_2 emissions. Several CCS projects, mainly related to the transport and storage of fossil-based CO_2 are underway, including storage related initiatives of the Porthos and Aramis projects (both in the Port of Rotterdam area), long distance CO_2 transport facilities (such as the Delta-Rhine Corridor pipeline and the Delta-Schelde CO_2nnection) and the (open access) CO_2 storage/transport terminal CO_2Next on the Maasvlakte (Port of Rotterdam), where liquefied CO_2 can be delivered by ships and barges, for storage via pipeline (as part as Aramis network) under the North Sea or by shipping to sites elsewhere, in particular to Norway.

[9] The potential European capacity for CO_2 storage is much larger (around 134 Gt CO_2), mainly in saline aquifers.

Monitoring of CDR

Monitoring, Reporting, and Verification (MRV) is the processes ensuring that CDR interventions provide measurable, transparent, and accountable carbon removal and at the same time minimize unintended ecological and socio-economic impacts. Across CDR techniques, the MRV systems should aim to quantify net carbon balance, assess permanence, detect potential leakages, and evaluate environmental side effects; report these impacts in a transparent and timely fashion; and undergo regular review to verify their accuracy and efficacy. Reporting and verification are related to general governance and administration of CDR and are not treated further in this chapter, which instead focuses on the monitoring requirements for different types of CDR.

Measuring how much carbon is in a sink at a given time is critical both for quantifying removals and for understanding and mitigating the risks of realized and future CDR projects. Such monitoring is particularly critical for systems where the amount of carbon stored is expected to change over time, such as with enhanced weathering, biochar, and any CDR system involving a living ecosystem. In some cases, stored carbon can be directly measured, such as with geologic storage and forests. However, tracking carbon stored in dispersed media, such as with biochar, enhanced weathering, and most forms of ocean CDR, is more challenging. In these cases, only indirect monitoring or estimation may be possible. Feasibility of monitoring itself is also a concern, and different tools will be needed for project-based monitoring without undue burden, as well as landscape-level monitoring (e.g., via EU Forest Observatory (JRC, n.d.) type projects) to validate project-level CDR estimation. Overall, governance of monitoring —and maintaining—stored carbon for potentially thousands of years is not financially and legally straightforward, as jurisdictions and finance systems typically change over these time horizons.

Durability vs monitorability of carbon storage media

	Low durability	High durability	Uncertain durability
Low monitorability	Consumable products Plastics	Dissolved bicarbonate Marine Sediment	Biochar [1] Marine biomass Wetlands[3]
High monitorability	Short-lived biomass	Geologic storage Stationary mineralized CO_2[2]	Trees[3] Soil[3] Coastal revegetation[3]

1: Biochar decays over time, though some fraction may have long-term stability. Decay rates are contingent on biochar composition, soil temperature, and biochar-soil interactions.

2: Either in rock formations or in long-life structures. Note that manmade materials suitable for mineralisation, such as concretes or slags, are typically only able to store CO_2 because CO_2 was earlier released from that material, e.g., in the calcination of limestone into lime and CO_2 in which cases the stored CO_2 does not represent CDR.

3: Storing carbon in ecosystems requires continuous management to prevent losses due to disease, fire, erosion, and land use change. Estimating above- and below-ground carbon stocks is technically a mature field of research, however doing so accurately for any given plot of land is a labour-intensive process.

Monitoring systems for CDR typically rely on a combination of field observations, sensor networks, modelling, and geospatial data (e.g., remote sensing) to realize a spatial-temporal assessment of the impacts of a given system. However, the design and complexity of monitoring frameworks vary substantially between CDR techniques that are potentially related with their differences in system boundaries, carbon storage pathways, and associated uncertainties. Robust and transparent monitoring is critical for supporting credible reporting, enabling comparison across CDR options, and informing policy, investment, and governance frameworks.

Forests

The integration of ground-based measurements (e.g., forest inventories) with remote sensing and geospatial analysis provides the foundation for monitoring of forest-related CDR approaches by enabling consistent, spatially explicit estimation of biomass and carbon stocks across spatial scales and over time. In this context, geospatial analysis includes the integration, upscaling, and harmonisation of multi-source data to map and monitor carbon stock dynamics wall-to-wall enabling also the detection of changes. This is critical for quantifying net carbon fluxes and understanding system dynamics (Gibbs et al., 2007). monitoring also supports the assessment of potential leakage, indirect land-use change, and trade-offs with food production and biodiversity. Therefore, geospatial monitoring systems support evidence-based policy and investment decisions where CDR targets are verified which are reported in a robust and transparent way in line with IPCC and EU guidelines. Remote sensing and geospatial analysis are relevant for the planning and monitoring of these forest-based CDR methods, because they enable finding suitable areas, assessing forest structure, disturbance, and growth dynamics in order to track management impacts and carbon stock changes in spatially-explicit ways (Hansen et al., 2013; Koch, 2010). Geospatial monitoring can help mitigate risks related to site selection, reversal events due to disturbances like fires, and leakage, while reducing uncertainties in carbon accounting through continuous tracking of forest growth and carbon stocks. Key research gaps remain regarding long-term carbon permanence under climate change and trade-offs with biodiversity, water resources, and other ecosystem services.

Peatlands, wetlands, and coastal restoration

The quantification of changes in greenhouse gas fluxes and hydrological properties is the focus of monitoring for peatland and wetland restoration. This is critical to assess the long-term greenhouse gas impact of the rewetting that frequently entails both reduced carbon dioxide emissions, and increased methane emissions (Günther et al., 2020). The balance between different greenhouse gases and the generally dynamic nature of wetlands and peatlands make its monitoring requirements relatively complex, which typically include field measurements and hydrological monitoring (IPCC, 2022b; IPCC, 2014). Geospatial analysis and remote sensing are also increasingly used to map inundation, surface moisture, and land-use changes.

Determining how much carbon is being stored by wetlands is a particular challenge. Wetlands often occur at river estuaries, trapping carbon-rich sediment released upstream. In wetlands, such as peatbogs, this phenomenon is of less concern. Key research gaps remain in quantifying long-term net greenhouse gas balances, including the trade-off between reduced carbon dioxide emissions and increased methane emissions, as well as attributing carbon accumulation to local ecosystem processes versus external sediment inputs.

Soil carbon

The high spatial variability of soils, small changes in time, and measurement uncertainties make the monitoring of soil carbon storage challenging. They rely mostly on field sampling, monitoring networks, and process-based models (see also IPCC, 2003). Geospatial and remote sensing are increasingly integrated, which enable the upscaling of point-based soil measurements to larger scale estimates as well as monitoring of drivers of soil carbon changes such as management, vegetation cover and dynamics. Monitoring can help mitigate risks related to carbon reversals by tracking soil carbon changes and their drivers over time. However, the effective integration of the diverse data sources remains a challenge to assess long-term durability of stored carbon and the reliable upscaling, also in the Netherlands where soil monitoring programs and dense agricultural data exists.

Biochar

While emissions from biochar production, including biomass storage and biochar transport, are highly monitorable, this traceability largely ends at the point of application. Post-application monitoring remains limited with uncertainties still regarding its long-term stability and effect on other carbon stocks (e.g., soil carbon). Monitoring biochar carbon in soil is challenging due to its intermingling with soil carbon and susceptibility to erosion. While different methods for estimating stored carbon as biochar have been proposed, there is currently not a scientific consensus on how to estimate what fraction of biochar carbon will be stored for a given length of time. Further, accurately estimating emissions of biomass sourcing and any related land-use changes for the cultivation of crops or forests (Smith et al., 2016) is particularly challenging, particularly when using imported biomass.

BioCCS

The highest uncertainties in bioCCS monitoring of are related to biomass sourcing, particularly when using imported biomass, as described for biochar, above. With regards to the CCS component of bioCCS, the carbon flows and energy use of capture, transport, and storage of CO_2 can be directly measured, which makes monitoring relatively straightforward compared to other CDR techniques. Other aspects of monitoring include the assessment of storage sites prior to use and the long-term monitoring of potential leakages. In general, subsurface monitoring technologies (e.g., seismic and pressure measurements) are available

and enable tracking of CO_2 movement and storage integrity. Monitoring can help mitigate risks related to biomass sourcing, supply-chain emissions, and CO_2 leakage through feedstock traceability and direct measurement of capture, transport, and storage processes. Key uncertainties remain regarding indirect land-use change associated with biomass production and the long-term governance, liability, and monitoring of geological CO_2 storage.

DACCS

The CCS components of DACCS have the same monitoring considerations of CCS for bioCCS addressed above. Remaining uncertainties primarily relate to life-cycle emissions, including the potential carbon emissions and temporal variability of energy supply, upstream emissions from sorbent production and degradation, and infrastructure-related emissions, which need to be taken into consideration to ensure net carbon removal.

Enhanced weathering

The monitoring of enhanced weathering is challenging, as the transfer from silicates (in soil) to ocean needs to be tracked (Beerling et al., 2025). Further, weathering is also a gradual process that is difficult to track how minerals dissolve, which makes it one of the hardest steps to monitor according to Hartmann et al. (2013). Consequently, current proposed monitoring techniques rely on a combination of different proxy measurement techniques including soil and water chemistry, laboratory analysis and geochemical models (Beerling et al., 2025; Hartmann et al., 2013). Key uncertainties remain due to slow reaction rates, limited direct observability of mineral dissolution, and attribution of alkalinity changes to interventions.

Ocean CDR

Monitoring of ocean CDR is complex and method dependent. All forms of ocean CDR are currently associated with substantial scientific uncertainties, which is particularly the case for biotic ocean-based approaches, such as macroalgae sinking and ocean fertilisation, where CO_2 uptake is realized through biogeochemical processes where it is difficult to separate the influence of human action from natural processes. Monitoring of ocean CDR also requires the monitoring of changes in ocean chemistry (e.g., alkalinity, dissolved inorganic carbon) and the effect on related ecological functions (e.g., nutrients, phytoplankton community structure) (Ho et al., 2023; Halloran et al., 2025), for which further research is needed across ocean CDR pathways. For abiotic CDR where the theoretical chemistry is well understood, such as DOCCS and ocean alkalinity enhancement, monitoring may require a combination of local measurement and conservative modelling to account for broader ocean impacts. However, direct monitoring of removals is unlikely to be possible.

Key ethical concerns for CDR

The ethics of CDR is an emerging sub-field in climate justice. This chapter provides an overview of some of the most important ethical issues raised by CDR that have been discussed in the literature, including climate justice, emissions "overshoot", mitigation deterrence, and procedural justice.

Climate justice

Climate change is widely acknowledged to raise concerns of injustice, including unequal distribution of risks and harms across geographies and generations, the creation of 'winners' and 'losers' from climate mitigation policies, the costs of climate adaptation, and compensation for loss and damage. In general, climate change presents a problem of **skewed vulnerabilities**, in which those who contributed least are the most vulnerable to climate impacts (Gardiner, 2011, p.31). The importance of justice is reflected in the UNFCCC principle of "Common but Differentiated Responsibilities and Respective Capabilities", which is commonly thought to reflect two important principles in climate ethics, the **polluter pays principle (PPP)**, and the **ability to pay principle (APP)** (Hayward, 2012). While the PPP states that the costs of climate policies borne by agents should be proportionate to their contribution to climate change (based on contribution to both present and historical GHG emissions), the APP supports that the costs of climate policies borne by agents should be proportionate to their ability to bear them (based especially on financial and technological considerations). Although the PPP and the APP primarily imply a duty to pay for emissions reductions, adaptation, and loss and damage measures (Bourban, 2023), another implication for climate or mitigation policies is that the burden of extracting GHG emissions from the atmosphere should rely primarily on those agents that are the most responsible for past and present GHG emissions and/or those that are the most financially and technologically capable of contributing to CDR. The potential for 'carbon majors' to benefit from CDR projects supported by public funding runs counter to the spirit of the PPP. If CDR policies are to be aligned with climate justice, nations with the requisite wealth and governance capabilities must not reward such actors when others with negligible carbon footprints can undertake CDR projects (Lenzi et al., 2023).

A key distinction in the climate justice literature has been made between "justice as fair burden sharing", which is about wealthy nations and individuals doing their fair share in funding climate policy (typically by following the PPP, the APP, or a combination of the two principles), and "justice as the avoidance of harm", which is about avoiding harms to basic human rights or human needs (cf. Caney, 2014). Harm avoidance involves giving priority to the protection of basic needs and human rights, which involves ensuring that the poorest do not bear costs of the climate transition (cf. Shue, 1992). Because the global carbon budget for limiting warming to "well below 2°C" is small and rapidly shrinking (IPCC, 2022b), protecting subsistence and human rights implies the transfer of finance and technologies to the poorest people to avoid locking in further emissions (Shue, 2019). This is especially relevant in the case of developed countries, such as the Netherlands. The explicit climate policy goals of most wealthy industrialised nations such as the USA, EU

members, and Japan fall far short of any reasonable interpretation of a fair global allocation of mitigation burdens (Holz et al., 2018:127). Fulfilling their climate responsibilities requires developed countries to contribute to mitigation opportunities in other countries. Developed countries therefore have a dual mitigation duty: in addition to domestic emission reductions, they must pursue enhanced international cooperation to facilitate global mitigation efforts, including under the form of CDR.

Importantly, when pursuing their mitigation policies, The Netherlands and other developed countries should (1) include CDR knowledge and technology in their technology and research transfers to other countries, (2) consider the impact of their resource use for CDR (and mitigation more broadly) in the context of a fair allocation of resources, and (3) not extract the climate value (such as carbon credits for offsets) of the CDR projects to which they contribute in other countries, but leave this value with the implementing country.

Issues related to imported biomass and burden shifting need to be considered from a global justice perspective, paying particular attention to international supply chains, resource extraction, land use, and the risk that CDR infrastructures reproduce environmental sacrifice zones and unequal distributions of risks and benefits across regions and communities.

Emissions 'overshoot' and justice

The ethics of CDR is related to the issue of emissions **overshoot**, which is a phenomenon in climate models in which slower mitigation is compensated for by larger removals of emissions through CDR later in the century (Malm and Carton, 2024) and involve a period where warming exceeds the intended target temperature.

Overshooting raises concerns of harm avoidance justice. The GHGs emitted in a period of overshooting will have harmful effects so long as they remain in the atmosphere. As the IPCC recognises, the 'Risk of severe impacts increase with every additional increment of global warming during overshoot (high confidence)' (IPCC, 2022a: 20). In short, the substitution of mitigation now with planned CDR later in the century increases the probability of foreseeable, avoidable, and irreversible harms to people vulnerable to climate impacts. Furthermore, Integrated Assessment Models (IAMs, i.e., the models which provide primary inputs into IPCC reports) do not generally include or estimate the implications of an extremely hazardous 'Hothouse Earth' situation emerging from current business-as-usual emissions trajectories (Steffen et al., 2018: 8254). Of course, such an outcome would violate human rights and basic interests, especially those of the most vulnerable. The large-scale implementation of CDR presumed in overshooting scenarios also raises concerns with harmful side effects of techniques that compete for land, water, and with other ecological functions, such as bioCCS (Shue, 2017; Lenzi, 2018; Bourban, 2026).

Box 2—Why is there so much CDR in IAMs?

Integrated Assessment Models (IAMs) are a tool used in climate research used to explore "possible futures" by linking models of economic behaviour to models of earth system behaviour and specifying constraints (e.g., resource availability) and goals (e.g., an emission or temperature target) to optimize for. But model outcomes are completely dependent on the assumptions and data inputted into the model.

A substantial share of IAMs assessed in the IPCC's Sixth Assessment Report (AR6) assume continued GDP expansion and apply cost-optimization to identify global "least-cost" mitigation pathways. Furthermore, discounting of future costs—assuming actions in the future will be cheaper than they are today—is a common economic modelling practice that can strongly influence model results without necessarily reflecting reality. While analytically useful, this creates a form of "growth lock-in": mitigation strategies are selected to minimize disruption to economic growth, privileging technological substitution over structural change.

As a result, not all mitigation options are equally "on the table": post-growth or low-demand pathways remain marginal, and demand-side changes (such as reduced consumption or sufficiency measures) are significantly underrepresented further amplifying modelled reliance on CDR. The AR6 reports wide ranging cost estimates for CDR, highlighting underlying uncertainties. Engineered options such as BECCS and DACCS are generally higher-cost and uncertain at scale, while nature-based approaches appear cheaper in the short-term, but face limits related to land, permanence, and ecological trade-offs. Across scenarios, especially those consistent with 1.5°C, IAMs project substantial deployment of CDR often reaching net-negative emissions later in the century. This apparent "necessity" of CDR is to a significant extent an artefact produced by the model: IAMs often combine limited near-term mitigation with stringent long-term temperature targets, generating a gap that is filled by large-scale CDR in the second half of the century. Continued economic growth, constrained mitigation options, and limited behavioural change together produce scenarios in which CDR becomes indispensable not necessarily because it is physically unavoidable, but because the models are configured in ways that make it so: alternative assumptions (e.g., earlier mitigation or lower demand) could significantly reduce CDR dependence.

Overshooting also raises concerns of fair burden sharing. Assuming perfect implementation of large-scale CDR, it has been argued that a period of overshoot can allow more time for poverty alleviation through economic development (Morrow and Svoboda, 2016). However, this raises the risk of a policy 'gamble' on large-scale CDR transfers risk to the vulnerable and to future generations, particularly if it proves impossible to scale up to the levels of CDR often seen in IPCC modelling (Shue, 2017; Lenzi, 2018; Bourban, 2026). A large overshoot would lead to a severely unjust allocation of climate burdens by transferring the costs of implementation, management, and side effects of CDR to young people and future generations, while avoiding present opportunities to deeply decarbonize our economies.

Finally, there are two major problems with the assumption that it would be possible to recover from an overshoot. The first problem is that it might be economically, technologically, politically, or biophysically infeasible to remove the excessive GHG emissions from the atmosphere. Second, even if it was possible to do so, there would still be climate impacts during the overshoot period on ecosystems, with increased risks for infrastructure, low-lying coastal settlements, ecosystem-based adaptation measures, and associated livelihoods. Such impacts could be irreversible, typically if they include the crossing of critical tipping points in the climate system, such as permafrost thawing, weakening of land and ocean carbon sinks, and Amazon forest dieback. In other words, an overshoot of the global carbon budget could lead not long-lasting or permanent effects on the climate system.

Box 3—Overshoot or high-emissions world?

A key question is whether current trajectories reflect temporary overshoot (where temperatures exceed targets like 1.5°C before later declining) or a more persistent high-emissions world. Overshoot scenarios assume that large-scale carbon removal and sustained mitigation will eventually bring temperatures back down, but this outcome is uncertain and may not occur if structural constraints limit decarbonization.

This tension was evident at the 2025 overshoot conference hosted by the International Institute for Applied Systems Analysis in Vienna, where participants were invited to answer a live poll on their phones about when temperatures might return below target levels. Notably, "never" was not an option. This omission highlights a tendency within parts of the integrated assessment modelling community to assume eventual return from overshoot.

Mitigation deterrence

A further important ethical concern is **mitigation deterrence**, i.e., the deferral of mitigation by either the implementation of CDR in practice, or merely the availability of CDR in modelling. An overriding concern among ethicists is that current mitigation will be delayed or avoided on the promise of CDR, even if this is merely a model result (Shue, 2021; 2017; Lenzi, 2018; 2021; Bourban, 2026). In integrated assessment models (IAMs), the availability of CDR leads to "mitigation obstruction by design" (Lenzi, 2018: 2): CDR inevitably displaces some near-term emissions reductions measures in these climate models, since scenarios aim to minimize mitigation costs over the century, and the availability of CDR measures lowers the aggregated costs of mitigation. In one comparison, near-term mitigation is greater by 9.1 Gt CO_2 by 2030 when CDR was excluded (Lenzi, 2018: 2). The urgency of immediate emissions reductions can therefore be artificially reduced in mitigation policies that rely on modelling scenarios in which the promise of (unproven) future CDR leads to less aggressive mitigation measures. Politically, CDR may be used as an excuse to delay mitigation decisions, especially when policymakers are not really committed to ambitious climate targets.

For these reasons, the policy aims of CDR should be subject to moral analysis to ensure that they align with the demands of justice—both in terms of fair burden sharing and harm avoidance. Shue (2021) distinguishes between CDR aimed at (a) enhancing current mitigation; (b) remedying past emissions; or (c) rescuing stranded assets. In Shue's judgement, which is echoed by most climate ethicists, aiming to use CDR in line with (c) is morally impermissible. Instead, policy uses of CDR aimed at enhancing current mitigation or remedying past emissions are morally permissible, so long as this does not supplant near-term mitigation.

Mitigation deterrence is related to two other ethical issues (Shue, 2017; Lenzi, 2018). The first is the problem of "betting" on CDR: relying on CDR to compensate for delayed mitigation is a high-stakes gamble. There is a risk that policymakers decide to bet on the availability of large-scale CDR in the future, even though these measures are largely unproven at scale and may not be feasible or safe to implement as needed. If CDR cannot

be scaled up as assumed, whether it is for technical, financial, or biophysical reasons, future generations may face severe consequences, including the need for even more drastic measures or the abandonment of climate targets. The second related ethical issue is that of **hubris**, or overconfidence in humanity's ability to control complex natural systems through large-scale interventions like CDR (Lenzi, 2018). Overestimating our ability to implement CDR safely and at a large scale could lead to unforeseen negative consequences, including ecological disruption and failure to achieve climate goals. Overestimating technical and epistemic abilities to scale up CDR measures in the future might come with an underestimation of the probability of failure, as well as an underestimation of what this failure would imply for future people.

Procedural justice

Procedural justice emphasizes the importance of inclusive and fair decision-making processes, ensuring that all stakeholders, especially marginalized groups, have a voice in climate-related decisions (Bourban et al., 2026). This raises the following questions: who ought to decide whether or not to research, develop, and deploy CDR measures? And what would a fair decision-making process look like in the case of CDR? Three main aspects are worth mentioning here (Preston, 2013).

First, the views of populations vulnerable to the social and environmental impacts of CDR must be incorporated. This implies involving them directly or through legitimate political representatives in the decision-making process leading to the implementation of CDR projects. For example, in the EU context, CDR can be implemented by member states in accordance with the **all affected principle**, in decision-making concerning the siting locations of CDR facilities. This would imply that all those who are significantly affected by a political decision related to CDR should have an opportunity to participate in, influence, or be represented in the making of that decision. Second, some form of consent, at least from the representatives of those affected by the deployment of CDR, is a minimal requirement of a just procedure. Third, stakeholder input is relevant not only regarding the question of whether or not to proceed with a CDR project, but also the questions of how to balance CDR efforts with emissions reductions efforts, how rapidly to ramp up CDR when it is scalable, how to most effectively evaluate the impacts of CDR, what to set as targets, and which political entity (or entities) should take charge.

Existing governance structures and mitigation deterrence risks

A climate technology is never detached from the political and economic world in which it is envisioned or embedded. On the contrary, many technological 'solutions' to address climate change—from hydrogen and carbon capture and storage to carbon dioxide removal—have powerful lobbies behind them from polluting companies or oil states that stand to lose from a rapid and just phaseout of fossil fuels (Gulden and Harvey, 2025). Zooming out a little, we live in a world where technological solutionism —that is, seeing the climate and ecological crisis as a problem we can solve through market-driven environmental policies and technological innovation—remains the dominant framework despite decades of failure to reduce global greenhouse gas emissions or halt the further destruction of nature by technological means alone (Malm and Carton, 2024; Fressoz, 2025; Stoddard et al., 2021).

Mitigation deterrence from CDR development and deployment is an existing phenomenon, as will be detailed in this chapter. Some policymakers are willing to slow mitigation efforts once they become politically difficult while using discussions about CDR to try to convey to citizens that they are still on top of the climate crisis. Some businesses use CDR to 'greenwash' their operations while investing as little as possible in financially costly transformative change. For both groups of actors, technological fixes that guarantee climate neutrality on paper are a welcome distraction from present action on climate change. Even scientific experts risk being caught up in this conundrum if their research on CDR—even when conducted in good faith—is used to stabilize the illusion that everything can remain largely unchanged.

Carbon credits and the voluntary carbon market

At present, supply and demand for CDR is driven by voluntary carbon markets. A growing number of start-ups and project developers are pursuing CDR approaches, covering nearly all of the technologies mentioned above. In voluntary carbon markets, these companies and other organizations sell carbon removal credits, which typically are intended to represent a quantity of net removal. These credits are often used to support voluntary climate commitments, including net-zero targets. This is typically done via offsetting: using the CDR credit to compensate for emissions occurring elsewhere. For example, an organization may purchase carbon removal credits and claim that the removals balance part of its own emissions. Large technology companies, notably Microsoft, has emerged as the largest corporate purchasers of carbon removal credits and have played a major role in stimulating demand for emerging CDR technologies. However, supply is not currently matched by demand, with 1.4 M t of CDR delivered by suppliers against 49 Mt of CDR credit purchased by buyers since 2019 (CDR.fyi, n.d.).

While offsetting can create financial flows for CDR, it remains controversial because of concerns that it may reduce incentives for direct emissions reductions (see sections on mitigation deterrence) and because emissions and removals may differ in their timing,

permanence, and broader environmental impacts. Moreover, quantification of removals is provided by private third parties, and certified CDR credits can vary widely in their estimation methodologies, risk management, and governance requirements.

Further, in the voluntary carbon market, removals are used to offset emissions based on a buyer's willingness to pay rather than the difficulty of decarbonisation. It is also the buyer who chooses what type of credit they use to offset which emissions, which makes climate impact claims incomparable with each other. To counteract the variety in credits and claiming, several voluntary standards (e.g., the Greenhouse Gas Protocol and Science Based Target Initiative) provide competing protocols for credit accounting, offsetting, and reporting.

The voluntary carbon market logic has influenced how governments are exploring how CDR can be incorporated into formal climate policy frameworks. Within the European Union, discussions are ongoing regarding the role of carbon removal in climate policy, including the creation of crediting and accounting standards for CDR credits and the possibility of their future integration into the EU Emissions Trading System (EU ETS). However, an offset crediting-based governance architecture requires that CDR be treated as a private-actor pay-for-results commodity, which can skew quantification incentives and exacerbate challenges of managing risks and uncertainties, particularly given the need for long-term maintenance and monitoring of stored carbon. The potential of alternative governance logics, such as a "central carbon bank" (e.g., Rickels et al., 2022; Edenhofer et al., 2023) or a removal obligation (e.g., Bednar et al., 2024), or more broadly, those that view CDR as a form of public waste management with limited availability and long-term liability, should also be considered.

The use of CDR by industry

Mitigation deterrence occurs in the world of business at least as much as in the political world. In economic terms, deterrence predominantly shields the past and ongoing investments in fossil fuels from becoming stranded assets, although the implication of achieving global climate targets will be that such assets will have no value at some point in the future (Malm and Carton, 2024). Such assets only retain their value when we transition away from fossil fuels very slowly—if at all. The promise of future removals is used to ensure that the envisioned decline in coal, oil and gas is not too steep. As far back as 2013, civil servants from the Dutch Ministry of Economic Affairs internally acknowledged that Carbon Capture and Storage (CCS) technologies—on which multiple CDR options are premised—are meant to protect the balance sheet of fossil fuel companies and their investors noting that "high carbon stocks and investments are worthless in a carbon neutral world" and that, as a consequence, "without CCS, such a climate neutral world or phaseout would not be possible (the write-offs on their balance sheet would then be too big)" (Van der Ploeg, 2022).

The political effort to protect the current investment regime aligns strongly with the way the industry itself delays or blocks meaningful action. Looking back on the decarbonization strategies of fossil fuel companies eight years after the Paris Agreement (2015) reveals

what intentional mitigation deterrence looks like in business. In business practice, mitigation deterrence is the phenomenon of using CDR pilots and promises as a strategy to maintain or expand fossil fuel production. The mitigation strategies of American oil and gas majors ExxonMobil and Chevron and their European counterparts Shell and Total, showed one thing very clearly: none of the net-zero strategies of these four fossil fuel companies included an ambition to actually reduce fossil fuel production, distribution and consumption. Instead, the dominant feature of their scenarios and pathways was to offset emissions through the purchase of cheap and old emissions-avoidance projects (Trencher et al., 2023; 2024). Other companies—American big tech companies being prominent among them—have a similar strategy of using carbon dioxide removal projects to offset their expansion of gas-based electricity plants to satisfy their increasing energy needs (Beatty, 2026; Joppa et al., 2021; Temple, 2025).

In recent years, technology-based removal projects have entered the purview of oil and gas companies. The biggest DAC facility, for instance, is currently built in Texas by Occidental Petroleum (Occidental Petroleum, 2023). After taking over DACCS company Carbon Engineering, Occidental Petroleum began to use the facility to pump CO_2 back into the earth for enhanced oil recovery. Close to ninety percent of the CO_2 that is captured from point sources, the CO_2 captured from the air is used to extract more fossil fuels from existing oil fields instead of downscaling oil production. With more than a billion-dollar worth of public investment, the company markets the extracted fossil fuels as 'net zero oil' thereby greenwashing its fossil fuel operations (Milman, 2023; Occidental Petroleum n.d.). Mitigation deterrence is the explicit objective as Vicki Hollub, the CEO of Occidental, made clear in a presentation: "We believe that our direct capture technology is going to be the technology that helps to preserve our industry over time" because it "gives our industry a license to continue to operate for the 60, 70, 80 years that I think it's going to be very much needed" (Lefebvre, 2023).

Through public outreach, like the illustrations from ExxonMobil below, fossil fuel companies help to further spread industry narrative to a broader public (ExxonMobil, 2022, 2024; Genetti, 2024). This form of mitigation deterrence does not stand on its own; it is "enabled by a media ecosystem that facilitates the promotion and circulation of narratives and imaginaries to an ever-wider audience" (Markusson et al., 2024). In society as it operates today, moreover, (fossil fuel) companies are "in a privileged position vis-a-vis other societal groups, because they can use the power of money to disseminate their visions and target influential constituencies like people working in research, investment, and policy" (Markusson et al., 2024). Powerful actors in the petrochemical industry, for instance, have developed a storyline where carbon removal is linked to ideas of circularity. This "circular carbon imaginary", scientists warn, "risks delaying climate mitigation by rendering alternative mitigation pathways undesirable". Instead of considering options of downscaling unnecessary production this imaginary works towards "reconciling increased production, carbon neutrality and circular economy in a vision of a circular carbon economy, framing the climate crisis as an issue of carbon management" (Palm et al., 2024).



ExxonMobil outreach for CCS and direct air capture (Genetti, 2024; ExxonMobil, 2022)

CDR in national and international policy

The starting point for a discussion on CDR regulation lies in the Paris Agreement, particularly Article 4.3, which calls for the "highest possible ambition" from participating countries. This principle has recently been reinforced by an advisory opinion of the International Court of Justice (ICJ, 2025:84), which clarifies that Nationally Determined Contributions (NDCs) are not purely discretionary. Rather, they are expected to be progressive, build on previous commitments, and collectively align with the goal of limiting global warming to 1.5°C. In this sense, countries are not entirely free to set arbitrary targets but are expected to continuously strengthen them in line with scientific necessity. The Court's reasoning also suggests that a standard of due diligence applies, meaning that states are expected to make serious and sustained efforts toward achieving the highest possible level of ambition.

This interpretation implies a more demanding obligation, namely that states must carry out a thorough and credible assessment of their mitigation options (Schönfeld and Rogelj, 2025). Such assessments cannot remain abstract or purely economy-wide; they increasingly require a sectoral perspective that identifies where emissions can realistically be reduced and where they are likely to persist. In many cases, however, this level of detail is still missing—for example, in the case of agricultural emissions (Neumann, 2025). This gap becomes especially important when considering so-called residual emissions, meaning those emissions that are difficult or impossible to eliminate and would therefore require CDR to reach net-zero targets.

Available evidence suggests that countries, like major corporations, fall short in this regard. Studies such as Buck et al. (2023) and Smith et al. (2024) show that NDCs do not consistently or transparently assess residual emissions, and similar shortcomings can be

observed in corporate climate strategies (Arendt, 2024). As a result, the boundary between what should be reduced directly and what is deferred to future removal remains unclear, leaving room for strategic ambiguity.

This ambiguity becomes problematic when viewed through the lens of the mitigation hierarchy, which prioritizes reducing the production of greenhouse gases above all else. CCS, which can used both for fossil CO_2 (which does not result in CDR) or atmospheric CO_2 (e.g., bioCCS, DACCS) does not prevent the generation of CO_2 but captures and stores carbon after it has been produced. In doing so, it creates what can be described as "Schrödinger's carbon" [10]: stored CO_2 is treated as equivalent to CO_2 not produced, but whose ultimate climate impact depends on future conditions such as long-term storage integrity, monitoring, and political support, which can never be wholly certain (Arendt, 2026).

Current policy trajectories further amplify these concerns. Many CDR approaches — especially nature-based ones, but even those involving CCS—carry some degree of reversal risk, which does not apply to conventional emission reductions. At the same time, policy frameworks increasingly envision a large-scale, for-profit, and relatively unconstrained CDR market (Grubert and Talati, 2023). Mechanisms under Article 6.4 of the Paris Agreement, as well as emerging regulatory frameworks in regions such as the European Union, risk expanding these markets without strictly limiting buying to actors with genuinely hard-to-abate emissions. This raises the risk that carbon removals are used not out of necessity, but as a convenient substitute for reductions that would otherwise be possible, including so-called "luxury emissions" for example from cruise ships or private jets.

Importantly, many of these shortcomings cannot be explained by a lack of knowledge. Rather, they reflect constraints related to feasibility, scalability, and entrenched power structures, which tend to weaken rules on durability, additionality, and environmental safeguards. The effectiveness of offsetting mechanisms has been repeatedly questioned (Probst et al., 2024), and CCS has failed to deliver at scale (Kazlou et al., 2024), yet both continue to play a central role in policy frameworks. This persistence suggests that short-term political and economic considerations often outweigh scientific evidence in climate policymaking. It is also reflected in the disproportionate influence of for-profit actors in consultation processes under Article 6.4 of the Paris Agreement and in the development of certification frameworks for carbon removal in the European Union (Losi et al., 2026). Addressing these issues requires both policy change and political will. Some of these aspects, but not all of them can be supported through research.

[10] Schrödinger's cat illustrates the paradox of quantum superposition: a cat in a sealed box is considered both alive and dead, with its state determined by a quantum event. Similarly, carbon dioxide allocated to carbon capture and storage in models effectively occupies multiple possible states (emitted, securely stored, or leaking) but here the outcome depends not on a quantum trigger, but on sustained finance, governance, and political will, which remain uncertain or insufficient. We will only know decades to millennia from now.

Mitigation deterrence risks in Dutch and European governance

Mitigation deterrence risks are very real in the climate policies of the European Union. The EU, scientists demonstrated, "has already made a choice against the strict separation of emission reductions and removals" in the case of nature-based mitigation targets (Brad and Scheider, 2024). As such, carbon removals can be used to offset greenhouse gas emissions that nations or companies are unwilling to reduce. The European Commission also considerably weakened the ninety percent reduction target for 2040 at the end of 2025 by allowing international carbon credits to contribute to up to 5% of the reduction target (Guillot, 2025). The conditions for these international credits are currently unclear—the only known criterion is that they should be of "high quality". In doing so, the European Commission went against the advice of its own board of scientific advisors and opened the door for Member States to further slowdown their emission reduction efforts (European Scientific Advisory Board on Climate Change, 2025).

Despite the insistence on prioritizing emission reductions, the combination of missed reduction targets and high CDR targets showcases that mitigation deterrence risks are present in Dutch political practice. Former Minister for Climate and Green Growth, Sophie Hermans (VVD), began to emphasize the importance of CDR at the same moment when the government's own environmental assessment agency warned that the chance of meeting more immediate reduction targets for 2030 had fallen below five percent (PBL, 2025; Buitenhof, 2025). The Dutch CDR roadmap subsequently included high levels of carbon dioxide removal in 2040 indicating that a full sixth of future emissions could possibly be offset in such a manner (Rijksoverheid, 2025). According to Prof. Heleen De Coninck, member of Dutch Scientific Council on Climate Change (WKR), this CDR target was very high indeed: "At the WKR we were looking at this and thought: this means that the emissions are still pretty high. You have not reduced emissions very significantly then. So, our first response was: try a little harder at reducing emissions" (Crezee, 2025).

Further evidence for the risk of deterrence comes from scientific studies and freedom of information requests concerning the reasons why certain states foreground certain climate technologies. The prominence of CCS in climate policy, for instance, is shown to be shaped by strategic interests as much as by climate concerns. Countries with strong historic ties to the fossil fuel industry as well as access to suitable geological storage sites—such as the Netherlands and Norway—are particularly active in advancing CCS (particularly under the sea, close to the coast), as it allows them to leverage existing subsurface resources and position themselves as hubs in an emerging carbon management market (Rodriguez, 2023; Lefstad et al., 2024; Witteman, 2021). As prominent CDR options are predicated on CCS technologies, this raise concerns that technological preferences for CDR are equally driven not (only) by mitigation effectiveness, but (also) by economic interest and state capture by the fossil fuel industry.

Managing liability of CDR risks

Questions of durability and reversal risk are especially challenging as the likelihood, timing, and magnitude of potential future carbon losses are inherently uncertain. This creates challenges for assigning liability and developing effective risk-management mechanisms. Robust monitoring is therefore essential. However, monitoring only has value if it is linked to meaningful consequences: where a credited removal is reversed, the corresponding credit should be revoked, replaced, or otherwise compensated for, which is not the case in existing crediting schemes. Without such mechanisms, a credit may continue to be treated as representing a valid climate benefit despite the underlying carbon having been released back into the atmosphere. This raises important questions about who bears responsibility for detecting reversals, maintaining monitoring systems, and providing replacement removals when reversals occur. These challenges are particularly pronounced for nature-based removals. The durability of carbon stored in forests, soils, and ecosystems depends on factors that are often difficult or impossible for project developers to control, including future temperature pathways, droughts, wildfires, pests, disease outbreaks, and changing land-use pressures, as well as continued management practices. As climate change intensifies, some of these risks may increase, creating uncertainty about the long-term permanence of stored carbon. This complicates both the quantification of reversal risk and the design of liability and insurance mechanisms intended to manage it.

While the insurance sector may attempt to engage with these risks, meaningful coverage would likely require actors with substantial reserves of removal credits to act as backstops—entities that do not currently exist. Existing approaches, such as buffer pools in forest-based offset systems, are often undercapitalized (Anderegg, 2025) and are not well suited to technical CDR, where uncertainties around long-term durability are even less well understood. While insurance products for large-scale CCS projects are beginning to emerge, these primarily cover operational, environmental, and financial risks over limited time horizons. They should not be confused with guarantees of permanent carbon storage. The long-term liability associated with maintaining climate benefits over decades to centuries remains difficult to quantify, insure, and assign, raising important governance questions regarding responsibility for future reversals and remediation, including who can credibly bear risk and provide remediation.

Public acceptance and perceptions of CDR

How citizens perceive and respond to new technologies can have a substantial impact on the successfulness of the implementation of the technology (Huijts et al., 2012). This is also the case for CDR technologies. An important example is the past attempt to implement carbon capture and storage (CCS) under a Dutch municipality in the years 2007-2010. While the project was technically and financially feasible, and supported by national policy makers, it was halted by resistance by citizens and local and provincial policy makers (Brunsting et al., 2011; Feenstra et al., 2010). Since then, no CO_2 storage under land has taken place in the Netherlands. Meanwhile offshore storage below the seabed is currently being developed and expected to be operational soon (Gasunie, n.d.).

In literature, **public acceptance** has been defined as "behaviour that enables or promotes (support) the use of a technology, rather than inhibits or demotes (resistance) the use of it" (Huijts et al., 2012:526). This could, for example, be expressing support for a technology, rather than protesting against it. The term **public acceptability** reflects an attitude towards the technology (Huijts et al., 2012). Finally, 'perceptions' are the more specific beliefs and concerns about CDR. Most studies measure public acceptability and perceptions (like all studies discussed below), with the unspoken underlying assumption that these influence actual behaviour—public acceptance—to a considerable extent.

Public awareness of CDR and media attention

Studies on CDR acceptability and perceptions show that awareness of CDR technologies is often not high. Fink and Ratte (2024) find, for example, that German coastal residents are frequently unaware of measures that can remove atmospheric CO_2 except for afforestation measures and storing CO_2 in ecosystems. Other studies also report that Western publics have not heard of or have little awareness of, for example, ocean CDR measures (Merk et al, 2023b) direct air capture (Scot-Buechler et al., 2024), or enhanced weathering technologies (Spence et al., 2021). This means that studies aiming to measure and understand public acceptance may include many missing responses, uncertain opinions, or non-sensical responses. Researchers may also choose to first provide information before measuring public acceptability (e.g., Scott-Buechler et al., 2024), leading to more informed, and possibly more stable, opinions. However, information does not necessarily change the average opinion on a specific CDR option (e.g., make it significantly more positive or negative), as is often assumed, but it may in some cases (Tvinnereim et al., 2026). Low awareness of CDR may also mean that people are currently not be well able to give their voice about CDR *policies*. It is thus important to continue engaging publics and incorporating their views in decision making (see also Spence et al., 2021), while providing them with high-quality information (Dunwoody, 2021).

A few studies analysed how CDR is discussed in the media as that information influences public opinion formation. Media attention for CDR has grown exponentially, according to Repke et al. (2024), reporting from Twitter data. They find that conventional CDR methods, which in their study included soil carbon sequestration, ecosystem restoration,

afforestation/reforestation and blue carbon, receive the most positive sentiments. Media coverage varies between presenting CDR as a critical solution versus as a risky, unproven technology, and further emphasizes its potential benefits for economic development, energy security, and the environment (Swain, 2025). Through such information, media coverage may increase public awareness of CDR and steer it in a certain direction.

Acceptance of CDR options and psychological predictors

Although there is limited awareness of CDR technologies, studies do present insights on how people in a specific country or region evaluate the different CDR options, using larger representative or non-representative samples of respondents. The findings suggest, that people in general tend to evaluate ecosystem-based approaches like habitat restoration, coastal restoration, afforestation, reforestation, but also biochar more positively than more technical approaches, such as bioCCS, DACCS, or enhanced rock weathering (Bellamy, 2022; Jobin & Siegrist, 2020; Lee et al., 2025; Low et al., 2024; Malakar et al., 2025; Merk et al., 2023b; Nawaz et al., 2023). Familiarity with these approaches and perceptions of CDR options as more "natural", better for the environment and future generations, and as more effective for limiting climate change influence these evaluations. At the same time, more technical approaches are perceived as more uncertain and risky options (Bellamy, 2022; Lee et al., 2025; Low et al., 2024). Acceptance levels of soil carbon storage and use of wood for construction seems to score more in the middle (Bellamy, 2022; Sweet et al., 2021). Ocean alkalinity enhancement and ocean fertilisation were found to be evaluated less positively than DACCS, due to concerns about impacts on ocean ecosystems (Cox et al., 2024; Nawaz et al., 2023).

Levels of public acceptance and acceptability vary depending not only on the technology, but also on the cultural context, and who you ask, and are therefore influenced by a range of factors. Most studies have been conducted in Global North countries, with the Netherlands sometimes being included (e.g., Baum et al., 2024; Lee et al., 2025). Few studies include and compare findings with those in Global South countries (e.g., Baum et al., 2024). Various psychological or cultural factors have been found to influence the level of acceptance of CDR, as supported by multiple studies:

Climate concern/worry and environmental self-identity. Perceived severity and urgency of climate change is positively associated with evaluations of ocean CDR, including coastal restoration, offshore direct air carbon capture and storage, ocean alkalinity enhancement and ocean fertilization (Nawaz et al., 2023). Belief in anthropogenic climate change is positively associated with support for direct air capture (Buechler et al., 2024). Stronger climate worry has been found to lead to both stronger positive and negative emotions towards CDR technologies, which means that these technologies could be quite polarizing particularly among the more climate-worried (Cox et al., 2024). Similarly, people who identify themselves as environmentally friendly are found to view CDR overall as more favourably, resulting in increased support; and at the same time, they perceive CDR as riskier, leading to lower support (Malakar et al., 2025).

Technology optimism. Technology optimism is positively associated with evaluations of ocean CDR, including coastal restoration, offshore direct air carbon capture and storage, ocean alkalinity enhancement and ocean fertilization (Nawaz et al., 2023).

Perceived benefits and risks. Perceived benefits of CDR have a positive effect on evaluations of CDR, and a stronger effect than perceived risks, which have a negative effect (Jobin & Siegrist, 2020; Malakar et al., 2025). Bringing jobs could increase acceptance of direct air capture (Buechler et al., 2024).

Perceived naturalness/tampering with nature. When people perceive a CDR technology as more natural, they tend to have a more positive stance towards it, while more aversion to or concerns about tempering with nature leads to a more negative stance towards the technology (Jobin & Siegrist, 2020; Malakar et al., 2025; Sweet et al., 2021).

Trust. Trust in various actors plays an important role in public acceptance. For example, people are concerned about leaving CDR in the hands of private interests (Bellamy, 2022). Higher trust in institutions predicts less comfort with various ocean CDR options with the exception of coastal restoration. Meanwhile, another study shows that a higher level of trust in industrial, scientific, and governmental actors is positively associated with public support for CDR technologies, including biochar, enhanced weathering, soil carbon sequestration, BECCS, DACCS, ocean sequestration, and ocean fertilization, but not afforestation (Jobin & Siegrist, 2020).

Global differences. Global South publics are found to have more favourable views about potential benefits and express greater support for climate-intervention technologies than Global North publics. Additionally, Global South publics express more concern that climate-intervention technologies could undermine efforts for mitigation (Baum et al., 2024). Similarly, publics in Asian countries are more positive about ocean CDR, such as ocean alkalinity enhancement; macroalgae-based bioCCS, and macroalgae cultivation and sinking, than in Western countries (Merk et al., 2023a).

Specific concerns

Studies on acceptability and perceptions also provide more detailed insights into other specific concerns that some people have about CDR. Besides wanting to discuss practical questions related to feasibility (Tvinnereim et al., 2026), people are worried about the risks of transport and storage of CO_2, which happens for example with direct air capture and storage (Scot-Buechler et al., 2024) and they worry about the costs, especially considering the current cost-of-living crisis (Cox et al., 2024; Merk et al., 2023b). People are also worried about the duration that the carbon stays stored (Cox et al., 2024; Merk et al., 2023b), about the immatureness of technologies, and risks and near-term adverse effects (Tvinnereim et al., 2026). Furthermore, they find it important that negative environmental side-effects are avoided, such as monocultures in afforestation (Merk et al., 2023b). People feel that residual emissions should be offset domestically to take responsibility for the national emissions (Merk et al., 2023b). Specifically, for DACCS studies show that people find it important that renewable energy is used (Merk et al., 2023b). In contrast, the long-term

need for CO_2 uptake and storage is found to be less prominent in one study (Tvinnereim et al., 2026).

One concern for promoting CDR is that companies and people will be less supportive of actions and technologies that lower CO_2 emissions. Particularly Global South publics expressed concern, more than Global North publics, that climate-intervention technologies could undermine efforts for mitigation (Baum et al., 2024). People were worried specifically that direct air capture allows companies to continue pollutive practices meanwhile greenwashing their public image (Scott-Buechler et al., 2024). Campbell-Arvai et al. (2017) also warned that promoting CDR may dampen support for climate change action particularly among the *unengaged*. Recent research on techno-optimism and environmental behaviours in general indeed suggests that techno-optimism, and particularly techno-fix attitudes, related to believing that technology can solve our problems and we do not need behaviour change, lower willingness to take pro-environmental behaviour (Cologna et al., 2024). Studies, therefore, warn against promoting CDR as it may undermine the much-needed carbon emission reduction.

Public participation

Besides instrumental, that is economical, reasons to take public acceptance into account, there are also democratic and ethical reasons to do so. For example, it is generally accepted that publics have a right to be informed and to be engaged (Fiorino, 1990) and often people say they want to be actively engaged in decision-making processes, but, in contrast, at the same time they limit their participation to getting passively informed from mainly traditional news sources (European Commission, 2025). Reasons for reluctance to participate more actively, citizens point out, are lack of time, knowledge and interest. However, public engagement processes when developing new technologies such as CDR contribute to more balanced decision-making processes. Therefore, next to analysing public perceptions and responses, it is important to include people's needs and wishes by means of co-creation and participatory methods, preferably at an early stage of the development. Early engagement can allow public considerations to substantially influence decision making about the details of the CDR project in place. Furthermore, it is possible to include needs from vulnerable groups, despite their reluctance in engagement.

Insights for the Dutch context

Most studies related to public acceptance were conducted in other countries than the Netherlands. Lee et al. (2025) reporting on public perception on afforestation and reforestation as well as DACCS after providing information, also separately reported on findings in the Netherlands. They found that afforestation is much more likely to be accepted than DACCS, and much more strongly so than for the other included European countries. Factors of influence on the evaluation of the two options were impacts on nature and the environment, impacts of future generations, effectiveness in limiting global warming, and impacts on other mitigation efforts. As it is known that details of specific

projects, provided information, local circumstances (such as the high population density and the polarised nitrogen debate in the Netherlands), and cultural factors can play a role in attitudes and perceptions, more research is needed to understand public perception, acceptability and acceptance of all the described CDR options and specific projects in the Dutch context.

Stakeholder perceptions on CDR in the Netherlands

Additional to the literature review, nine Dutch stakeholders were interviewed in April 2026, and a stakeholder workshop was held in May 2026. Of the interviews, four interviewees were industrial stakeholders, two came from academia, two represented NGOs and one was a governmental stakeholder. The following text provides a summary of the interviews' main findings. Although the limited number of interviews does not allow to reflect every possible opinion or position the findings do provide an overview of major recurring patterns.

On the necessity of carbon dioxide removal technologies

Carbon dioxide removal is seen by most interviewees as an eventual necessity. The need for CDR stems from two main reasons. First, the need to mitigate hard-to-abate emissions and second, the requirement for large scale negative emissions if a maximum of 1.5 degrees temperature increase compared to pre-industrial levels is targeted. The opinions regarding timing and scale of the deployment were more mixed. Most stakeholders do express several concerns or caution regarding rapid large-scale deployment of CDR. A majority agreed with the notion that CDR should not replace focus on reducing greenhouse gas emissions.

Several stakeholders mentioned that other mitigation efforts should be targeted first in terms of resource investment (capital, research capacity), whereas others stated that European wide research efforts should commence immediately to be ready for large scale deployment of CDR. CDR is viewed as more expensive and requiring more energy, resources and land use than all other mitigation measures. The intensity differs per type of CDR technology employed, but all have serious drawbacks on these aspects. Moreover, critics among the interviewees point out that the need for CDR stems from the IPCC models that are not including significant future emissions reductions because of major socio-economic changes. Advocates pointed out that even when taking the criticism into account, CDR will still be necessary to meet the Paris agreement targets as no action will be a more harmful scenario for future generations.

Carbon dioxide removal technologies in the Netherlands

In the context of the Netherlands, the high energy costs and land use competition are mentioned most frequently as major obstacles for CDR. Moreover, most forms of CDR have a relatively low technological readiness level, except for forestation. Considering these restrictions, most stakeholders mentioned bioenergy with carbon capture and storage (BECCS) as most scalable form of CDR in the Netherlands. Several interviewees raised concerns regarding the volatile, uncertain or too positively framed results of previous carbon capture and storage (CCS) projects. In their views, other forms of CDR should be pursued as well in research programmes to map their capture and deployment potential as

well as societal and ecological impact. Knowledge developments on CDR and pilot scale projects were mentioned as the biggest opportunities for the Netherlands. The Netherlands has a strong network of knowledge institutes with expertise in CDR as well as several start-ups in CDR, but the current knowledge is fragmented.

Monitoring, reporting, and verification

The monitoring, reporting, and verification of CDR were major concerns raised by the stakeholders. The voluntary carbon credits market is referred to as being controversial or as having controversial aspects. For example, aspects include double accounting of mitigated emissions, projects not being additional, and interference with human rights or local communities' livelihood in developing countries. Furthermore, for several CDR techniques interviewees raised concerns regarding the durability of the carbon stored. In current carbon crediting systems, decades-long stored carbon is not discriminated from carbon stored for thousands of years. Several stakeholders suggested a different crediting system for CDR specifically. Moreover, an independent organisation or committee should be charged with the verification to mitigate concerns related to undesirable incentives such as self-reporting or financial interest by the verification body in providing as many carbon credits as possible.

Greenwashing concerns

The concerns found in literature regarding greenwashing were corroborated by the stakeholders. Most frequently mentioned were the concerns for emissions mitigation deterrence, using high energy pathways for CDR while being powered by fossil fuels, embedding CDR in strategies without a clear view on its justification in terms of realistic scenarios considering social, economic, spatial and technical aspects, ecological risks, social justice and ethical risks. Moreover, not all types of CDR have a high level of CO_2 storage permanence which is not considered in most crediting schemes. Several stakeholders advocated therefore for these types of CDR to be deployed for other purposes with CO_2 capture as co-benefit.

Public perception and social acceptance

Most stakeholders agreed that citizens should be more involved in the public debate on CDR as well as in emerging CDR projects or initiatives. Up until now, CDR has stayed in academic, industrial and policy circles while public perception and acceptance can make or break a CDR project. The failed CCS project at Barendrecht was highlighted by several stakeholders as study case, in which lack of public inclusion and consequently resistance led to the failure of the project. The response to the current level of social acceptance of CDR was mixed. According to the interviewees, the level of social acceptance of CDR varies from low, unknown to the stakeholder, to context specific. Technical CDRs, especially (BE)CCS are generally perceived as something negative, whereas nature-based solutions are

perceived more positively. In general, interviewees thought that citizens are aware of reforestation and to some extent CCS, but other CDR technologies are relatively unknown. If CDR is going to be adopted and deployed on large scale, public debate is expected to have a large influence on the impact and level of CDR deployment. Domestic projects are expected to face resistance if it involves CDR technologies with no other co-benefits. Several stakeholders emphasized the need for including the public from an early stage in the project.

Ethics and social justice

The two main ethical concerns mentioned by the interviewees were, first, resource exploitation of developing countries by developed countries and second, exposure of future generations to the cost from deficient present emissions reduction.

The resource exploitation concerns of developing countries ("global South") by developed countries relates to land use for biomass growth, limiting local communities access to ecosystem services (food, biodiversity, livelihood). Moreover, concerns were raised regarding the misuse of certification systems without transparency and lack of additionality. Stakeholders advocated for verifiable local supply chains (the Netherlands and Europe) for CDR (such as for biomass inputs or CO_2 transport) if CDR would be implemented.

The ethical concern regarding future generations comes from the fact that future generations should not be held responsible for past greenhouse gas emissions and the effects of climate change, by being exposed to the resulting hazards and risks. Mitigation efforts for this ethical concern are challenging and politically sensitive. Stakeholders' views were also mixed on this topic. Some of the stakeholders viewed CDR as an additional cost for future generations while its deployment would stimulate mitigation deterrence. Others point out the cost of inaction to future generations, since they argued that the Paris agreement targets cannot be reached without implementation of CDR.

Research needs and recommendations

The diversity of results in CDR research shows that CDR is not a "plug and play" mitigation technology, but one whose efficacy is heavily dependent on the local context of implementation. In this section, first, research gaps are identified, and second, followed by recommendations for responsible governance of CDR. The research gaps identified below are illustrative and not exhaustive, and focus on the key questions for Dutch governance of CDR. In particular, they do not include the technical and scientific uncertainties for CDR techniques, which are specific per type of CDR and were identified in the chapters above. Furthermore, technical considerations for CDR cannot not be wholly separated from governance considerations, such as at the intersection of risk management. Therefore, particular attention is needed to research efforts that integrate technological, ecological, and social considerations of CDR deployment possibilities.

Research needed to reduce uncertainties, trade-offs, and risks of CDR in the Netherlands

Understanding the potential deployment of CDR in the Netherlands requires understanding the locally available resources and conditions that affect CDR suitability. In particular, detailed information is needed on the quantity and specific qualities of available land for dedicated and co-sited CDR, such as afforestation, peatland restoration, biochar, and enhanced weathering. These must be assessed for potential co-benefits and risks, which will be site specific, as well as monitorability, maintainability, and future resource competition. This assessment can be conducted in conjunction with a mapping of existing CDR initiatives in the Netherlands to understand the risk trajectory of those projects.

Further, climatic conditions have implications across CDR types, including in species selection for afforestation and biochar decay rates. Even (geo)chemical forms of CDR, such as DACCS and enhanced weathering, have CO_2 uptake efficiencies that are affected by the temperature and humidity of ambient air. Research is needed to understand how the climatic features of the Netherlands would affect CDR deployment across CDR types, and in particular account for future climate scenarios.

Another unresolved question is how CDR deployment interacts with other land-use transitions. This particularly regards agricultural emission mitigation (e.g., extensification, emission reduction policies) and whether combined strategies create real synergies or simply shift pressures across sectors (food, biodiversity, water). Overall, there is still limited ability to quantify trade-offs across carbon storage, biodiversity, water, food production, and energy systems in a spatially explicit way to support spatial planning. Further, for some forms of biological CDR (e.g., agroforestry, soil carbon storage, peatland restoration)—carbon storage may not be the optimal primary benefit.

More broadly, CDR research fundamentally needs to explicitly account for time. Aggregation of lifetime CDR impacts into single-point 100-year metrics is insufficient to understand how the different options can and cannot contribute to time-bound targets, such as a 2050

emission targets and a 2100 temperature limit. This requires research both into CDR itself as well as methodological research to expand life cycle assessment as well as greenhouse gas accounting metrics to account for time-explicit impacts and uncertainty. It is also important to consider that many types of carbon sinks—forests, soils, geologic formations—can saturate and therefore will not be available indefinitely. Assessing total sinks availabilities—and how they may be affected by climate change and demand competition—is a key gap for understanding the potential for CDR deployment in the Netherlands.

Across all CDR approaches, a key research gap is the development of consistent and scalable monitoring frameworks that can robustly quantify net carbon removals across heterogeneous systems. This includes improving the integration of field measurements, geospatial data, models, and industrial monitoring to ensure comparability across techniques, while adequately capturing life-cycle emissions, spatial leakage effects, ecological side effects (positive and negative), and long-term carbon permanence.

Finally, a critical look is needed at the models and metrics we use to evaluate CDR, as well as other climate change mitigation options. These methods, such as integrated assessment modelling, life cycle assessment, and technoeconomic assessment—embody assumptions about acceptable distribution of costs and benefits over time, present and future availability of resources, and how the climate will respond to given activities, and may rely on outdated data and assumptions of technology performance and costs. Understanding the influence of such assumptions and data sources on model results is a key first step towards more robust and transparent decision-making over CDR.

Research needed to improve clear, open and transparent governance of CDR in the Netherlands

Critical attention is needed to develop CDR governance structures that explicitly accounts for the risks and uncertainties of CDR and includes societal perspectives by means of stakeholder and citizen engagement of relevant groups. Such governance structures require additional research on developing policy pathways that are adaptive to changing risks and uncertainties, as well as robust liability mechanisms, and understanding of which CDR risks are independent or co-dependent.

Greater emphasis is also needed on placing CDR in the context of other demands for resources, both in modelling and in policy development, including for other mitigation options, as well as adaptation needs and other societal demand for resources, and how these may change over time. For example, in the Netherlands, the electricity grid is strained and expansion is slow, water availability is under stress, and land use is saturated. Modelling is needed to assess what resources may be available for CDR at what time, which needs to be contextualized with governmental policy goals for sustainable development, mitigation, adaptation, as well as infrastructure management.

Further, given restricted availability of resources as well as the heterogeneity of CDR implementation systems, it is important to establish selection criteria for a 'merit order' of

CDR opportunities available in the Netherlands that considers local resource availability, local technical and ecological synergies and trade-offs, expected removal rates, costs, and social considerations such as social acceptability and perspectives over fair distribution of risks and resources.

Research needed to address ethical aspects of CDR

From an ethical perspective, more research is needed to systematically integrate values and principles into CDR projects and activities, such as justice, informed consent, integrity, and respect for nature. This research needs to be carried out both in relation to CDR research and development and in relation to CDR deployment. At the level of research and development, approaches and methods such as ethics by design or value-sensitive design could be relevant starting points to bridge the gap; at the level of deployment, regulatory frameworks and operational guidelines would provide important insights into the conditions that would make CDR practices ethically acceptable. Each value and principle would need further research in this context. For instance, justice has many dimensions. And, although some dimensions are covered in this report and the literature, other dimensions, such as recognition justice, historical justice, ecological justice, and interspecies justice need to be included to reach a more comprehensive account of the conditions that would make CDR research, development, and deployment ethical.

Another important point is that the literature on CDR should engage more explicitly and more comprehensively with questions of epistemic plurality and knowledge systems. The framing of "responsible CDR" should not only rely on scientific, technical, and policy-oriented perspectives. There is room to further engage with Indigenous, relational, and situated understandings of human–nature relations, as well as broader questions of epistemic justice and whose knowledge counts in shaping climate futures.

In addition, since mitigation deterrence represents one of the most important (ethical) risks of CDR, more research is needed to find the conditions or requirement that would make it possible to avoid or at least mitigate the risk of mitigation deterrence in CDR policies and projects. This is especially important in a context where mitigation deterrence has already taken place, both at a national and international level: it is imperative to avoid future CDR policies and projects to further delay emissions reductions measures.

Finally, greater conceptual clarity is needed in scientific, political, and economic discourses on CDR. Two notions are especially relevant here. Since durability is a key feature of CDR, it is important to investigate normative assumptions behind common uses of the notion of "durability". How long should CO_2 emissions that have been captured be stored to meet the "durability" requirement? How long is long enough? Different responses to these questions might rely on different conceptions of intergenerational ethics. Likewise, it is important to examine the normative assumptions behind dominant uses of the notion of "residual emissions": what makes GHG emissions "residual", "hard to abate", or "unavoidable"? Who gets to claim residual emissions? This question might partially be answered by relying on

the distinction between subsistence and luxury emissions, but this distinction is itself a topic of ongoing debate.

Research needed for to support CDR governance and regulation

Several important governance questions remain insufficiently addressed and warrant further research. First, there is the question of defining residual emissions and highest possible ambition. Research is needed on how residual emissions should be defined, assessed, and governed in ways that are transparent, scientifically robust, and socially legitimate. This includes more comprehensive assessments of mitigation options across sectors, including demand-side measures that are often overlooked in policy and modelling exercises. Participatory processes involving civil society, affected communities, and other stakeholders are needed to develop for example roadmaps for residual emissions that can provide a credible basis for determining when and where CDR is appropriate. Such work is essential to ensuring that carbon removals remain complementary to, rather than substitutes for, ambitious mitigation efforts.

In addition, an important research question relates to CDR governance beyond carbon markets. Further research is needed into alternative governance models for supporting CDR that do not rely primarily on offsetting or carbon credit markets. This research includes examining public procurement, regulated carbon storage obligations, public infrastructure approaches, and other mechanisms that may support removals while avoiding some of the challenges associated with additionality, permanence, liability, and the fungibility of removals and emissions reductions. Comparative analysis of market-based and non-market approaches can help clarify the conditions under which different governance arrangements contribute to climate objectives.

Third, more research is needed into the accounting, durability, and liability of various CDR technologies. Existing accounting frameworks often struggle to reflect the distinctive characteristics of carbon removals, particularly uncertainties surrounding permanence, durability, reversal risk, and additionality. Further research is needed to develop accounting and governance approaches that adequately capture these differences and avoid treating carbon removals as fully equivalent to emissions that were never produced. This research includes questions of monitoring, long-term stewardship, liability, credit revocation, and the management of reversal and non-additionality risks over extended timescales.

The fourth research question that needs more scrutiny is related to the geopolitics, political economy, and policy stability of carbon removal. The future governance of CDR cannot be understood solely as a technical challenge. Climate policy is increasingly shaped by concerns related to economic competitiveness, industrial strategy, energy security, and geopolitical developments. Research is needed on how these dynamics influence CDR governance and how climate ambition can be maintained in changing political contexts. Particular attention should be paid to the limitations of voluntary governance arrangements

and to the role that states and public institutions can play in providing long-term policy stability and accountability

Finally, there is the question as to the power and influence of various actors to delay or block just and effective climate action (climate obstruction). More research is needed on the role of vested interests, incumbent industries, and other actors that may influence the development of CDR governance and deployment. It includes examining how different actors shape narratives around residual emissions, offsets, technological optimism, and climate ambition, as well as how power asymmetries affect decision-making processes. Understanding these dynamics is essential for ensuring that CDR governance contributes to climate mitigation objectives rather than reinforcing existing barriers to decarbonization.

Research needed to better understand societal needs and concerns

In order to increase inclusive and participatory decision making on CDR in the Netherlands, and to better understand under which conditions implementation of CDR projects is acceptable, it is important to understand how diverse audiences (including citizens, local communities, and other affected publics) perceive, evaluate and respond to CDR. This research applies to understanding audiences' views on CDR options in general, as well as related to specific CDR policies and projects. It is particularly important to understand what underlies publics' needs and concerns and what conditions, if any, can lead to acceptance, to be able to improve decision making on CDR.

Both qualitative and quantitative research methods, as well as mixed-method approaches, need to be pursued to gain in-depth understanding of views, perceptions and needs of citizens and local communities as well as representativeness for the Dutch population of those. Participatory methods are specifically often recommended in literature, to empower citizens to actively influence decisions affecting their lives. Media analysis studies analysing how different rationales and frames for conducting CDR, as well how different policies and technical options (including monitoring options) are portrayed, can provide insight on how the topic is discussed in the public domain, which will influence how citizens perceive and evaluate CDR.

It is of particular importance also to recognize and address the concerns of more vulnerable groups. As for example the costs of living are already very high for a considerable group of citizens, an important question to be addressed is related to the distribution of the costs of CDR projects. Since people elsewhere (e.g., in the global south, including the Dutch islands in the Antilles) are suffering from our historical CO_2 emissions, it is important to also take their perspectives into account. Participatory methods engaging local communities will facilitate deeper insight in their needs and wishes.

Recommendations for responsible governance of CDR deployment and research

Two of the main findings of the report are that (a) there are substantial ecological and political side effects of an insistence on, and possible scaling of, carbon dioxide removal while (b) current regulatory and responsible research and innovation frameworks fall short of reliably preventing such negative side effects. Many of the shortcomings are bound up with the fact that short-term political and economic considerations often outweigh scientific evidence and ethical considerations in climate policymaking and showcase the disproportionate influence of for-profit actors in political consultation processes and in the development of certification frameworks for carbon removals. As a consequence, rules on maximum mitigation efforts, minimal residual emissions, permanence of storage, double counting of removals and environmental safeguards tend to be significantly weakened.

Our report has assessed the current uncertainties of CDR systems and the risks of ecological harm and mitigation deterrence in the public and private sectors in sufficient detail to move beyond generic guidance in the undertaking of research. The academic community is increasingly cognizant, however, that policymakers and companies consistently fail in honouring their climate commitments and that thirty years of moving along risks implicated scientists in this failure. We see in the scientific community (including ourselves) that researchers' stance towards these principles ranges from an overall encouragement of their endorsement by all stakeholders to refusing further collaboration with policymakers and private partners until the principles are adhered to. To address these shortcomings, we propose that policymakers, research funders and researchers endorse the following six principles for responsible CDR governance and responsible CDR research.

Four principles for responsible governance of CDR deployment

Our report has assessed the current uncertainties of CDR systems and the risks of ecological harm and mitigation deterrence in the public and private sectors in sufficient detail to move beyond generic guidance in the undertaking of research. Following Honegger et al. (2021), we argue that the Dutch government should explicitly limit such risks by subscribing to a "governance principle for avoidance of over-promise and under-delivery" along the following lines:

1. **Demonstrate maximum mitigation ambition**. Although the report focuses on CDR, CDR cannot be isolated from climate policy as a whole. Current mitigation ambitions are largely restricted to subsidizing technological innovation and market-based solutions. Maximum ambition would include the honest consideration of – and serious experimentation with - all available policy measures, including those that are traditionally underrepresented, such as scaling down high-emitting economic sectors, demand reduction, and sufficiency measures.
2. **Restrict the role of removal in mitigation ambitions to a minimum.** Taken together, current regulation risks enabling an unconstrained expansion of CDR demand driven by private actors. This anticipation of technological fixes whose future availability

and impacts are still uncertain creates a high risk of delaying or weakening present action to reduce emissions. Net-zero targets should not assume a specific future availability of removals until these uncertainties are resolved, and the government should also explicitly consider the possibility that realizable domestic removals may be negligible, particularly given constraints on and competition for available resources such as electricity and biomass. Further, net-zero ambitions should be supported by transparent and differentiated targets and accounting for different greenhouse gases emissions and types of CDR, as these all have different intertemporal profiles of climate impacts and risks.

3. **Act out of social and ecological responsibility.** Both ecological and justice concerns require thorough consideration of the impacts—positive and negative—of CDR techniques beyond carbon storage, particularly for CDR that competes with agriculture or ecological functions for scarce land. In particular, CDR in ecosystems and agricultural lands should focus on maximising the ecological benefits rather than the quantity of carbon stored. Many of the CDR technologies discussed in this report have significant consequences for land-use and local communities in the Netherlands, as well as elsewhere. Although these technologies might be developed and/or implemented in the Netherlands, their export or resource demands might cause harm in other parts of the globe, particularly in the Global South. Further, net-zero ambitions should be supported by transparent and differentiated targets and accounting for different greenhouse gases emissions and types of CDR, as these all have different intertemporal profiles of climate impacts and risks.
4. **Respect procedural justice.** A responsible approach to CDR governance implies ensuring inclusive and equitable decision-making processes that both include all affected stakeholders, especially vulnerable populations, and enable their meaningful participation on fair terms. This requires research into public acceptance, perceptions and concerns, as well as public engagement and co-creation methodologies with local communities and affected groups from the start of the decision-making process. Ideally, this includes securing legitimate representation and consent from affected groups; transparent communication about risks, benefits, and uncertainties of CDR and other mitigation options; integrating stakeholder input across key decisions; and establishing robust governance frameworks before advancing deployment. This also entails deliberating not only on CDR as such, but also which emissions can be deemed "residual" and therefore be offset by CDR, remain, and according to what criteria, given the significant distributive and intergenerational implications of such decisions.

Two principles for responsible CDR research and innovation

The ethics of CDR—and climate justice more generally—not only concerns responsible governance and regulation od CDR deployment; it has clear implications as well for the funding of research and the public-private partnerships that may be supported or incentivised through such funding. With regard to responsible CDR research and innovation, the AGU (2024:12) writes that 'public and private funding of climate intervention research and experimentation should be completely transparent' and that 'researchers should maintain a clear separation between funders and the decision-making that goes into

conducting research'. Based on the findings of our report, we argue that transparency is a necessary but insufficient measure to ensure responsible research and innovation. We therefore argue for two additional principles:

5. **Responsible research funding.** Plans to fund research and innovation on CDR should not compete with existing funding for mitigation. Further, given the current technical and systemic uncertainties of CDR, funding for CDR research should also be predicated on transparent and public reporting of all findings and underlying data, which should be synthesized into the larger context of ecological and social impacts.
6. **Responsible research collaboration.** To limit mitigation deterrence risks, those private partners that have track records of (1) substantially contributing to GHG emissions and (2) undermining climate policies should not receive public financing to undertake CDR or be involved in publicly (co)funded CDR research and innovation consortia.[11] Accordingly, fossil fuel extraction companies with a track record of climate policy obstruction would be ineligible for public funding. By contrast, companies with limited past and present GHG emissions, companies rapidly moving away from fossil fuel investment, and/or companies with no record of climate policy obstruction could participate in public-private CDR initiatives.

[11] There is an argument that polluters could pay for the harm they inflict by investing in R&D, typically citing the polluter pays principle. The polluter pays principle, however, has a clear meaning in the scientific literature on climate and environmental harm: under this principle, a company with a high level of CO_2 emissions—or other form of pollution—has to pay for the full extent of their harmful activities and take responsibility of compensating the harm they have inflicted on human and non-human life. There is no mention in this literature that R&D investments count as a way of making up for (historical) emissions. These investments, for one, are usually very small in comparison to the level of profits that companies make and do not compensate for the actual loss and damage that is inflicted. In addition, company R&D investments in academic research are often intertwined with additional economic objectives such as gaining access to policymakers, influencing climate policies, determining the direction and results of research, and/or greenwashing company operations. Instead of R&D (co)funding, directly financing mitigation and adaptation efforts at scale would be the most obvious ways for such companies to make up for their historical harm.

Final words

The Netherlands has a legal and a moral obligation to neutralise its impact on global warming. To do so, all measures to mitigate greenhouse gas emissions deserve thorough consideration for how they can contribute to the Dutch portfolio of climate action. As we have illustrated, however, carbon dioxide removal is not a single silver bullet, but rather a diverse set of technology systems embedded within ecological systems, as well as within the economic context of competing demand for resources, the political context of climate action and inaction, and the social context of the distribution of climate harms and responsibilities, and public acceptance. The potential risks and benefits of a CDR system depend not only on the type of CDR broadly, but on the implementation specifics for each project.

Therefore, responsible governance of CDR starts with an honest acknowledgement of the risks and uncertainties of attempting to dramatically upscale these systems. These risks and uncertainties are technical (e.g., triggers for re-release of stored carbon), economic (e.g., competition for resources), administrative (e.g., quantification protocols), political (e.g., mitigation deterrence) and social (e.g., public acceptance and public engagement). Before any target for CDR upscaling can be credible, such uncertainties and risks must be reduced by further advances in research and in governance. Failure to do so risks unethically prioritising the uncertain possibility of future CDR over concrete near-term mitigation.

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