SCIENCE-POLICY BRIEF

Achieving Climate Neutrality and Paris Agreement Goals: **Opportunities for Ocean-Based Methods of Carbon Dioxide Removal**

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About

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Removing carbon dioxide from the atmosphere to reach net zero

There is a consensus in scientific climate research that humanity will only curb global warming and the resulting climate impacts if it reduces its carbon dioxide (CO_2) emissions to net zero. But even with ambitious climate policies, experts believe that we will still be emitting residual amounts of CO_2 (5 and 15 percent of current CO_2 emissions) by the middle of the 21st century, thus further driving global warming. These residual emissions will be generated, for example, in cement and steel production, in air and heavy-duty transport, but also in agriculture and waste incineration.

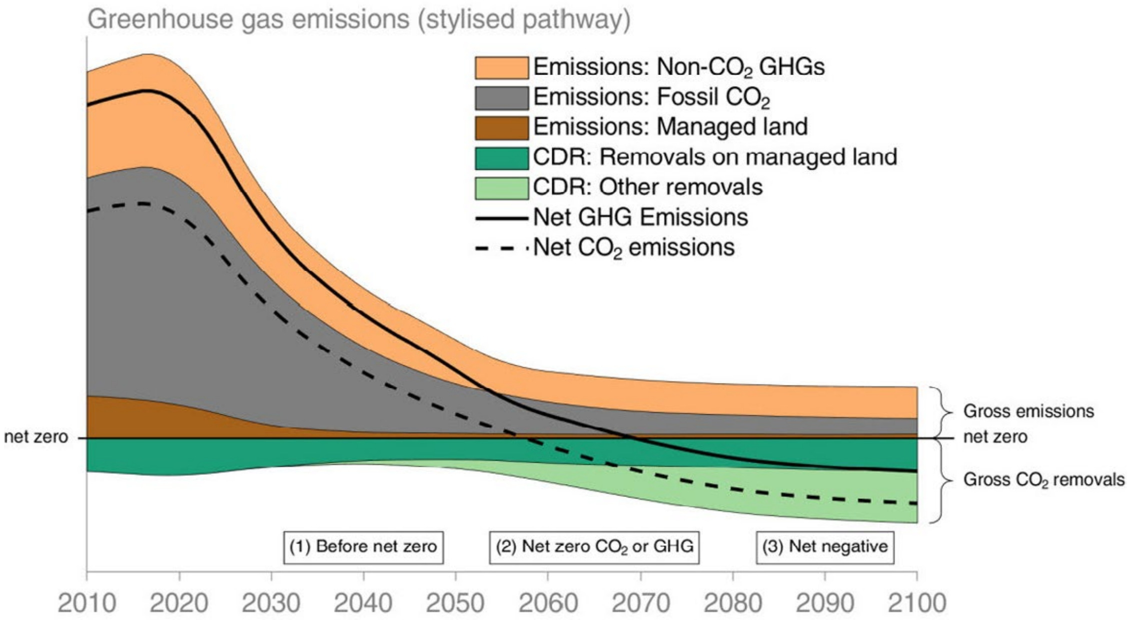

Figure 1: Roles of Carbon Dioxide Removal (CDR) in global or national mitigation strategies. Stylised pathway showing multiple functions of CDR in different phases of ambitious mitigation: (1) further reducing net CO_2 or GHG emission levels in near-term; (2) counterbalancing residual emissions to help reach net zero CO_2 or GHG emissions in the mid-term; (3) achieve and sustain net-negative CO_2 or GHG emissions in the long-term (Babiker, M. et al. (2022))

One solution to compensate these residual emissions is through targeted carbon dioxide removal (CDR) and storage (carbon capture and storage = CCS) processes.
The release of some emissions can be prevented if CO_2 is captured at the emission source and subsequently stored geologically. This is important for those industrial sectors that cannot currently avoid emissions of fossil origin. Moreover, there are several approaches to removing CO_2 from the atmosphere. **Many carbon dioxide removal processes investigated to date are land-based. However, ocean-based approaches and processes are being increasingly explored.** The ocean covers over 70 % of the Earth's surface and will be the predominant, largest long-term sink for man-made CO_2. These factors alone suggest that ocean-based CDR approaches should have at least as much – and potentially much more – CDR potential than land-based removal processes.

Why engage in ocean-based carbon dioxide removal?

The Earth's climate system uses physical, chemical, and biological processes to remove carbon dioxide from the atmosphere and store it on land, in the ocean, or in the geological subsurface. The world ocean utilizes these processes to such an extensive degree that it has buffered very large changes in atmospheric CO_2 concentrations throughout Earth's history. **Because of its natural CO_2 uptake capacity, the ocean is the major player in the global carbon cycle.** However, CO_2 uptake processes in the ocean and ocean floor occur on long time scales. Various CDR approaches could accelerate such processes and thereby increase the ocean's CO_2 uptake rate.

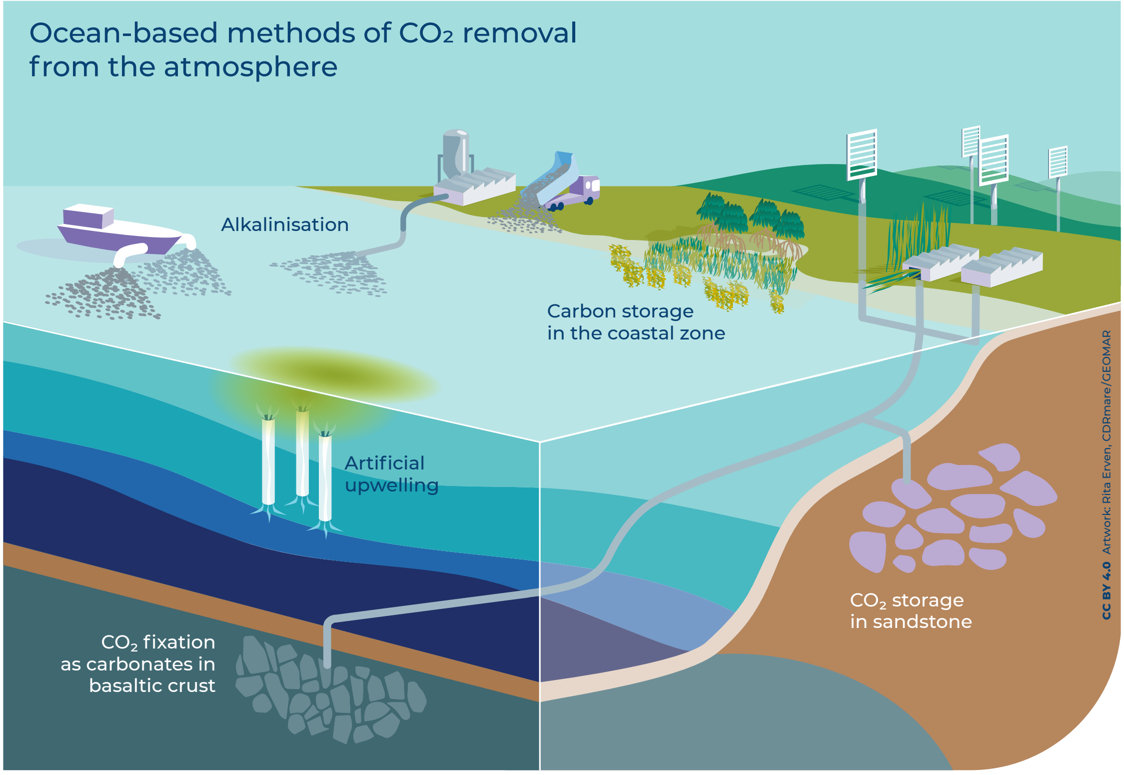

Figure 2: Illustration of ocean-based CDR processes that are being assessed within OceanNETs and CDRmare.

In the German research mission CDRmare (funded by the Federal Ministry of Education and Research) and in the EU Horizon 2020 project OceanNETs, researchers are investigating a broad spectrum of marine approaches to carbon dioxide removal and storage, focussing on methods and measures that appear promising at present. The scientists working on marine CDR in these projects view the ocean as a global, interconnected system: changes in one area may lead to interactions with other linked sub-areas and forms of use (e.g., fisheries or tourism). Only on the basis of a holistic research approach can the potentials, costs, and risks of human-enhanced carbon dioxide uptake by the ocean be realistically assessed. This also includes aspects such as social and political acceptance of such approaches and factors affecting these, affordability, societal impacts as well as possible risks and co-benefits, or implications for governance and policy.

It is important to understand which methods are applicable at all, under which local and global conditions they work, and which approaches have to be discarded. In this context, science has the task of providing public and transparent information for informed and inclusive decision-making. **Which solutions for countering climate change will be used in the future must be negotiated politically and in society in an open debate.**

What do models tell us about CDR and its impacts on climate change?

Earth system models are the primary tools available for investigating the response of the climate system to various forcings, for making climate predictions on seasonal to decadal time scales and for making projections of future climate over the coming century and beyond. **Our understanding and capability to model climate-carbon uptake interactions is improving so that we can build valuable and actionable knowledge for citizens, businesses, and governments.**

Earth system modeling studies of ocean-based CDR have been used to investigate: (1) the climate impacts and atmospheric CO_2 reduction efficacy of the approaches, (2) the issue of reversibility of climate change in an overshoot situation (average temperature increase above 1.5 °C or 2 °C), (3) approaches at large-scale over long time periods, (4) method specific side effects (both risks and co-benefits). Early studies have suggested that some approaches like ocean alkalinity enhancement have a great potential for CDR, while others, such as artificial upwelling have less CDR potential and large side effects. Although often idealized, this early work has been insightful and helped to direct and focus research efforts on specific CDR approaches. For example, leading to new laboratory and mesocosm studies of ocean alkalinity enhancement, which can in turn provide information to better model the approach.

Ocean Alkalinity Enhancement – a promising ocean-based CDR approach

Alkalinity is the capacity of a solution to neutralize acid. By increasing the alkalinity of the upper ocean, the carbon storage capacity of seawater can be enhanced and thus, more CO_2 can be taken up by the ocean.

Ocean alkalinity enhancement involves the addition of carbonate-containing minerals or alkaline solutions to the ocean, which then react with CO_2 and water, thereby de-acidifying the seawater.

There are several approaches to ocean alkalinity enhancement:

1) Alkaline rocks such as limestone can be mined to create lime, which could then be added directly to the ocean as mineral powder (ocean liming).
2) Another suggested approach is to react seawater with alkaline minerals through electrolysis in a chemical reactor (e. g. desalination plant) before releasing the alkaline solution back into the ocean.

Although models can simulate ocean-based CDR, until now, these approaches have largely been neglected in climate mitigation scenario projections. To understand the role of CDR in mitigation pathways, the inclusion of ocean-based CDR options is needed in the integrated assessment models that generate climate change scenarios. This will allow for more realistic simulations of ocean-based CDR. CDRmare and OceanNETs scientists are working on iterative loops between experimental work and models to better understand CDR and to improve models to allow better informed decision making processes. **Modeling teams have also been exploring how to use the models in conjunction with observational capabilities for monitoring, verification, and reporting (MRV) of ocean-based CDR.**

Governance and legal considerations of ocean-based CDR processes

Net-zero climate policies foresee deployment of atmospheric carbon dioxide removal with geological, terrestrial, or marine carbon storage. While terrestrial and geological storage are governed under the relevant domestic legal frameworks – including, but not limited to, mining law, land law, nature conservation law, and spatial planning law –, marine CDR approaches must comply with the requirements of international law, in particular those codified in the 1982 United Nations Convention on the Law of the Sea (UNCLOS).

To the extent that ocean-based CDR approaches are associated with the **introduction of substances into the marine environment** (e.g. in the cases of ocean alkalinity enhancement and ocean iron fertilization), these activities are regulated by the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (**London Convention/LC**) and its 1996 Protocol (**London Protocol/LP**). These international treaties substantiate the framework provisions codified in the UNCLOS with specific regard to the prevention, reduction and control of marine pollution from dumping. Importantly, in 2013, the Contracting Parties to the London Protocol adopted an amendment by which the scope of the Protocol was expressly extended to the regulation of "marine geoengineering". Applicability of the new permit regime established by the amendment to a specific marine geoengineering approach depends on whether the Contracting Parties have decided to include the activity concerned in the **new Annex 4** to the London Protocol. So far, only ocean iron fertilization is mentioned in this Annex. While the amendment has the merit of **being the first binding international regulation explicitly applicable to ocean-based CDR approaches, it has yet to enter into force.** It also remains to be analyzed whether the substantive requirements established by the new provisions, as well as the assessment framework concerning field tests included in the 2013 amendment, can be operationalized in a sufficiently flexible and at the same time precautionary way for ocean-based CDR.

Furthermore, the **complex and fragmented nature of international, regional and national ocean governance regimes and the transboundary nature of the marine environment,** create potential additional constraints to a larger-scale implementation of ocean-based technologies that have not been taken into consideration yet. These may impede larger-scale applications of such interventions with the ocean, or create trade-offs with other policy goals laid out such as biodiversity conservation – but possibly also supportive co-benefits. Such effects have been discussed in the literature at a broader scale, but a sound knowledge base of interactions across a larger set of ocean-based CDR with the current ocean governance system and including their relation to key principles such as the precautionary approach or ecosystem-based management is only now being developed by legal scholars within CDRmare and OceanNETs, also in the light of possible transformations of the current system for (larger-scale) applications of ocean-based CDR.

International bodies such as the Conference of the Parties (COP) to the Convention on Biological Diversity (CBD) have already dealt with ocean-based CDR on various occasions. Political negotiations within – and potentially across – existing governance structures are crucial in order for the governance process for ocean-based CDR to move along and to address open issues. In addition to these highly relevant international bodies, stakeholders other than States, e.g., from science, the general public and actors from the private sector, ought to be included for comprehensive decision-making processes with regards to ocean-based CDR. Particular attention must be devoted to the needs of future generations and, where applicable, the interests of vulnerable groups and indigenous communities affected by climate change. For example, non-governmental organizations could take on the role as advocates for marine life and other underrepresented groups when facilitating deliberations towards a "good governance" of marine CDR. The land-ocean-connection plays a significant role for many of the proposed technologies in terms of policy integration and stakeholder engagement.

Economics and carbon accounting

Very few cost estimates for ocean-based CDR exist and those that do are based on incomplete information. Moreover, full life cycle analyses of ocean-based CDR approaches have not yet been conducted and integrated assessments of climate-economy pathways have so far mostly overlooked ocean-based CDR approaches. Accordingly, improved integrated assessment of ocean-based CDR, addressing regional deployment scenarios and the feedback on marine ecosystems are required, to better understand their social cost.

A question of particular importance for European decision makers is **how European climate policy may play out in a setting that lacks full global cooperation.** Such an analysis of potential strategic advantages of ocean CDR with the support of decentralized integrated assessment models, needs to be defined and developed. The strategic role of ocean-based CDR in a world with limited international mitigation coordination needs to be analyzed. Furthermore, various ocean-based

CDR methods would be deployed under de-facto open access regimes and the common pool resource problems of various stakeholders, ranging from governments with removal targets to local coastal communities with other needs like for example sea-level rise protection or eutrophication mitigation should be addressed. Accounting for possible co-benefits, various ocean-based CDR methods provide social benefits in excess of carbon removal valued by carbon prices alone.

Still, the integration of ocean-based CDR requires comparison to emissions abatement on a carbon basis. Different accounting methods have been introduced to quantify the impacts of CDR methods. The review of existing accounting methods clearly shows that so far, the focus has been on projects with temporary storage since the majority of projects involved afforestation. For ocean CDR projects, and in particular ocean alkalinity enhancement, a major obstacle will be the verification of storage. Currently, there are no accounting methods available properly dealing with this issue. However, the **accounting questions should not be discussed in isolation from the climate policy framework** in mind. While for example, the current design of the European Emissions Trading System imposes rather high accounting requirements, the accounting requirements for extending the Land Use, Land-Use Change and Forestry (LULUCF) emissions to coastal habitats or in general for the inclusion of (ocean-based) CDR into intra-country-emission-trading under the effort sharing regulation seem more appropriate for ocean-based CDR. For example, it might be straightforward to assess the developments of blue carbon habitats (and in turn their protection and enhancement) against a business-as-usual benchmark and to derive removal supply or credit demand which would be comparable in terms of credibility to the treatment of afforestation under the LULUCF regulation.

Thus, CDRmare and OceanNETs systematically review, apply, and extend carbon accounting schemes to include ocean-based CDR and assess their appropriateness of assigning carbon credits to the various CDR approaches. Operational and economic costs, the social optimum for ocean CDR application, distributional implications, and strategic incentives of ocean CDR application are investigated as well.

So far, the research reveals that promising ocean-based CDR approaches with regard to cost are ocean liming (large potential), electrochemical ocean alkalinity enhancement in conjunction with the desalination of seawater (fairly easy add-on technology; environmental benefits), and when accounting for social co-benefits also blue carbon sink enhancement.

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OceanNETs is a European Union project funded by the Commission's Horizon 2020 program under the topic of Negative emissions and land-use based mitigation assessment (LC-CLA-02-2019), coordinated by GEOMAR Helmholtz Center for Ocean Research Kiel (GEOMAR), Germany. OceanNETs responds to the societal need to rapidly provide a scientifically rigorous and comprehensive assessment of negative emission technologies (NETs). The project focuses on analyzing and quantifying the environmental, social, and political feasibility and impacts of ocean-based NETs. OceanNETs will close fundamental knowledge gaps on specific ocean-based NETs and provide more in-depth investigations of NETs that have already been suggested to have a high CDR potential, levels of sustainability, or potential co-benefits. It will identify to what extent, and how, ocean-based NETs can play a role in keeping climate change within the limits set by the Paris Agreement.

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In order to support pathways to mitigate the increasingly drastic consequences of human-made climate change and to achieve the Paris Agreement goals, the removal of CO_2 from the atmosphere will be an important measure alongside massive CO_2 emission reductions.
The research mission CDRmare (CDR: Carbondioxide Removal – CO_2 removal) investigates whether and to what extent the ocean can play a significant role in the removal and storage of CO_2 from the atmosphere. It also considers the linkages with and impacts on the marine environment, Earth system, and society, as well as appropriate approaches for monitoring, attributing, and accounting for marine carbon storage in a changing environment.
The research mission will establish relevant assessment criteria and, in the long term contribute to, a Marine Carbon Roadmap for the sustainable use of marine carbon storage at regional to global scales, in close dialogue with stakeholders.

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