Prospects and Challenges of Investigating Ocean-Based Negative Emission Technologies

Insights from the OceanNETs Project

OceanNETs has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 869357.

Synthesis report

This OceanNETs synthesis report offers a condensed synopsis of major outcomes and key conclusions obtained from the different work packages of the project. It is designed to inform and engage scientists across a wide range of disciplines, thereby contributing to capacity building in the field of marine carbon dioxide removal (CDR). It synthesizes the complex findings of OceanNETs in a condensed format. Alongside the synthesis of key insights, the report provides direct references and links to the full suite of OceanNETs deliverables and peer-reviewed publications, enabling readers to further explore the underlying data, methodologies, and details of the analyses.

The introduction, which provides general information about the project, is followed by key messages that convey important lessons learned, points out significant findings, and provides recommendations for possible actions and research activities. Thereafter, the report provides a summary of insights documented in greater detail in OceanNETs deliverables and publications. That part is split into two thematic sections: **Section A** addresses **Society and ONETs**, and **section B** covers **Scalability and responses to ONETs (OAE)**. Each section is further divided into research topics, each of which first provides information on the research approaches and then describes key findings. This synthesis report closes with a series of synopses presented in the form of four ONET research briefs. They provide more complementary and comprehensive insights that go beyond the outcomes of OceanNETs by incorporating results from other relevant publications and reports that often emerged in parallel during the course of the project.

The references to OceanNETs publications and deliverables are marked **in blue**, with deliverables further distinguished from peer-reviewed publications by the inclusion of their deliverable numbers. References to external studies that enrich the overall synthesis are not marked by color. It is noted that few analyses are still in progress and will be published after the project has been closed.

OceanNETs is a project funded by the European Union's Horizon 2020 research an innovation programme under Grant Agreement No. 869357, 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 focused on analyzing and quantifying the environmental, social, and political feasibility and impacts of ocean-based NETs. OceanNETs helped closing fundamental knowledge gaps on specific ocean-based NETs and has provided more in-depth investigations of NETs that had already been suggested to have a high CDR potential, levels of sustainability, or potential co-benefits. The project's research activities served to determine how and to what extent ocean-based NETs can contribute to keeping climate change within the limits set by the Paris Agreement.

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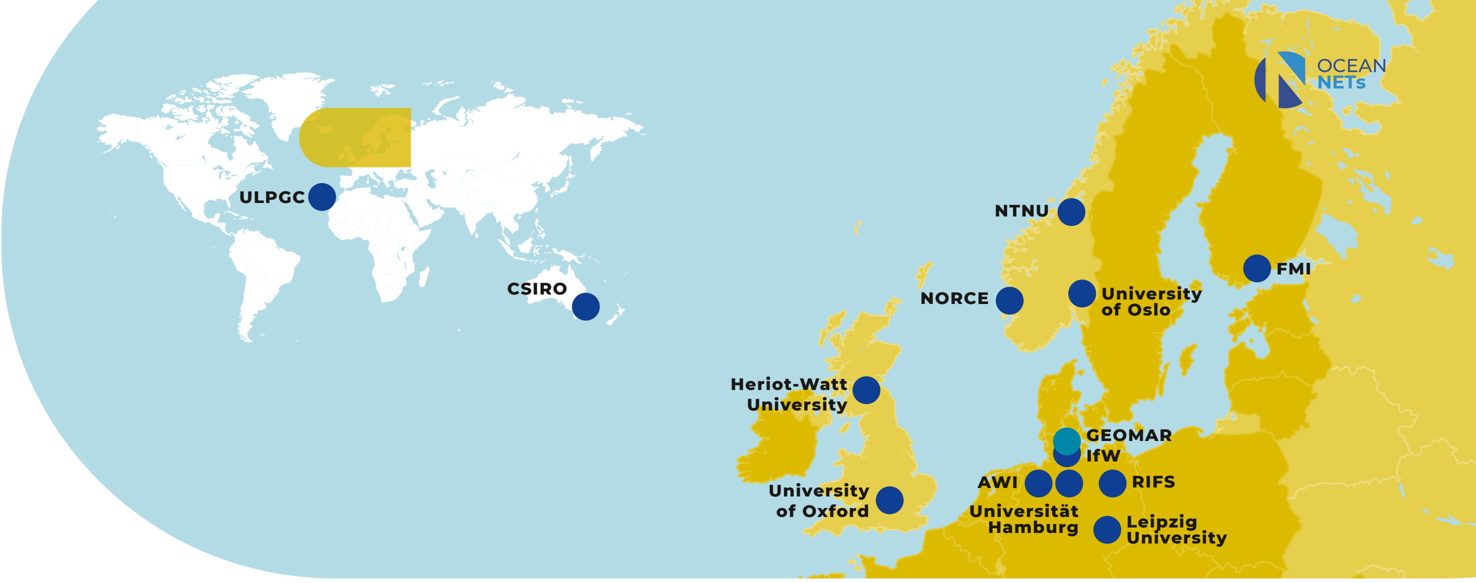

Imprint

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September 2025

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Acknowledgement

We sincerely thank Michela Tagliaferri (EU project officer), Monica Lupion (University of Buffalo, USA), and Christopher Pearce (National Oceanography Centre, United Kingdom) for their guidance and constructive comments on the draft synthesis report. Their input greatly improved the clarity of the report.

We deeply appreciate the valuable feedback and comments by David Koweek, Brad Ack and colleagues from Ocean Visions, Lydia Kapsenberg (CEA Consulting, USA), Steffen Swoboda (CDRatlas, Germany), Michael Steiger (Arizona State University, USA), and Christian Sarpey, which helped structure and strengthen the results presented in this synthesis report.

Suggested citation

M. Schartau, J. Schwinger, L. Röschel, B. Neumann, C. Merk, G. Andersen, W. Rickels, A. Perrels, P. Renforth, S. Fowler, N. Sánchez, L. Kittu, N. Suitner, M. Seifert, A. Sathyanadh, J. Hauck, S. Schäfer, H. Muri, J. Lezaun, D. Keller, H. Göhlich (2025): **Prospects and Challenges of Investigating Ocean-Based Negative Emission Technologies: Insights from the OceanNETs Project**, pp. 1-60, DOI: 10.3289/oceannets_d7.10-12

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Introduction

Contextual basis

There is broad scientific consensus that global warming must be mitigated and that effective strategies are required to reduce greenhouse gas emissions. To limit the increase in global average temperature to well below 2°C above pre-industrial levels, as proposed in the Paris Agreement (United Nations Framework Convention on Climate Change, UNFCCC, 2015), CO_2 emissions should reach net zero within the upcoming decades, between the years 2035 and 2070, as reported by the IPCC (2022b, Shukla et al.). According to the climate responses to the Shared Socio-economic Pathways (SSPs) assessed in IPCC (2023, Lee et al.), only in the scenarios with low and very low emissions (SSP1-2.6 and SSP1-1.9) are net-zero CO_2 emissions approached by 2070 and 2050 respectively. In case of such ambitious scenarios, Carbon Dioxide Removal (CDR) measures, using negative emission technologies (NETs), would then be needed to compensate up to 11 $GtCO_2$ residual emissions annually (Edelenbosch et al., 2024).

The ocean has already absorbed around a quarter of anthropogenic CO_2 emissions (Friedlingstein et al., 2022, 2023), which demonstrates its substantial storage potential. Various ocean-based NETs (ONETs) have been proposed to enhance the ocean's natural ability to sequester CO_2, which are therefore envisioned as potential marine CDR options. To become a viable option for contributing to the target of net zero emissions, ONET strategies must demonstrate a high potential for removing CO_2 from the atmosphere and offer credible pathways for implementation under various environmental and regulatory conditions. Such an undertaking is inherently complex, as it necessitates the integration of social, ethical, economic, and governance considerations, thereby calling for a holistic approach. Dealing with these diverse and interconnected challenges was the central motivation for the OceanNETs project, the first integrated European effort to investigate ONETs by combining natural and social sciences.

Project scope

The OceanNETs project has been dedicated to analyzing and quantifying the potential feasibility and impacts of ONETs. For this purpose, a transdisciplinary research approach was adopted that integrates expertise from the social, political, economic, natural, and engineering sciences as well as from experts and stakeholders, ensuring that diverse perspectives are heard and integrated. OceanNETs has been 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).

Prior to the launch of OceanNETs, it was already recognized that analyzing all known variants of ONETs in equal detail across disciplines would dilute the depth and usefulness of the findings. Instead, the project deliberately focused on a subset of ONETs (Figure 1) that had been previously identified as having either particularly high CDR potentials, enhanced sustainability, or notable co-benefits. This strategic focus allowed for more comprehensive and realistic investigations, ranging from public perception and governance challenges to operational processes, technical viability and environmental impacts. By concentrating efforts on topics where knowledge gaps were most pressing and societal relevance greatest, OceanNETs generated insights that are both scientifically robust and closely aligned with real-world conditions.

The research in OceanNETs was structured into three core themes (CTs): i) CT1 focused on social, governance, and socio-economic aspects, ii) CT2 explored scalability and responses to ONETs, covered by experimental studies and modeling that focused on ocean alkalinity enhancement (OAE), and iii) CT3 was a cross-cutting theme that addressed the techno-economic issues of various OAE approaches and their potentially feasible implementations. Project and data management were also assigned to CT3.

Under the umbrella of CT1, a portfolio of ONETs has been under investigation. The scientific approaches involved public surveys, interactions with stakeholders, literature research, as well as socio-economic integrated assessments and the analysis of carbon accounting schemes. Within CT2, potential impacts of OAE on the plankton ecosystem and geochemistry were investigated in two mesocosm experiments. Based on elaborated life cycle assessments (LCAs) and future economic growth projections, realistic scenarios of OAE were derived within CT3, which were then incorporated into Earth-system- and regional model applications in CT2. The greater emphasis within CT2 and CT3 on OAE helped to produce new, profound insights that more clearly exposed the realistic prospects and the associated limitations of OAE options.

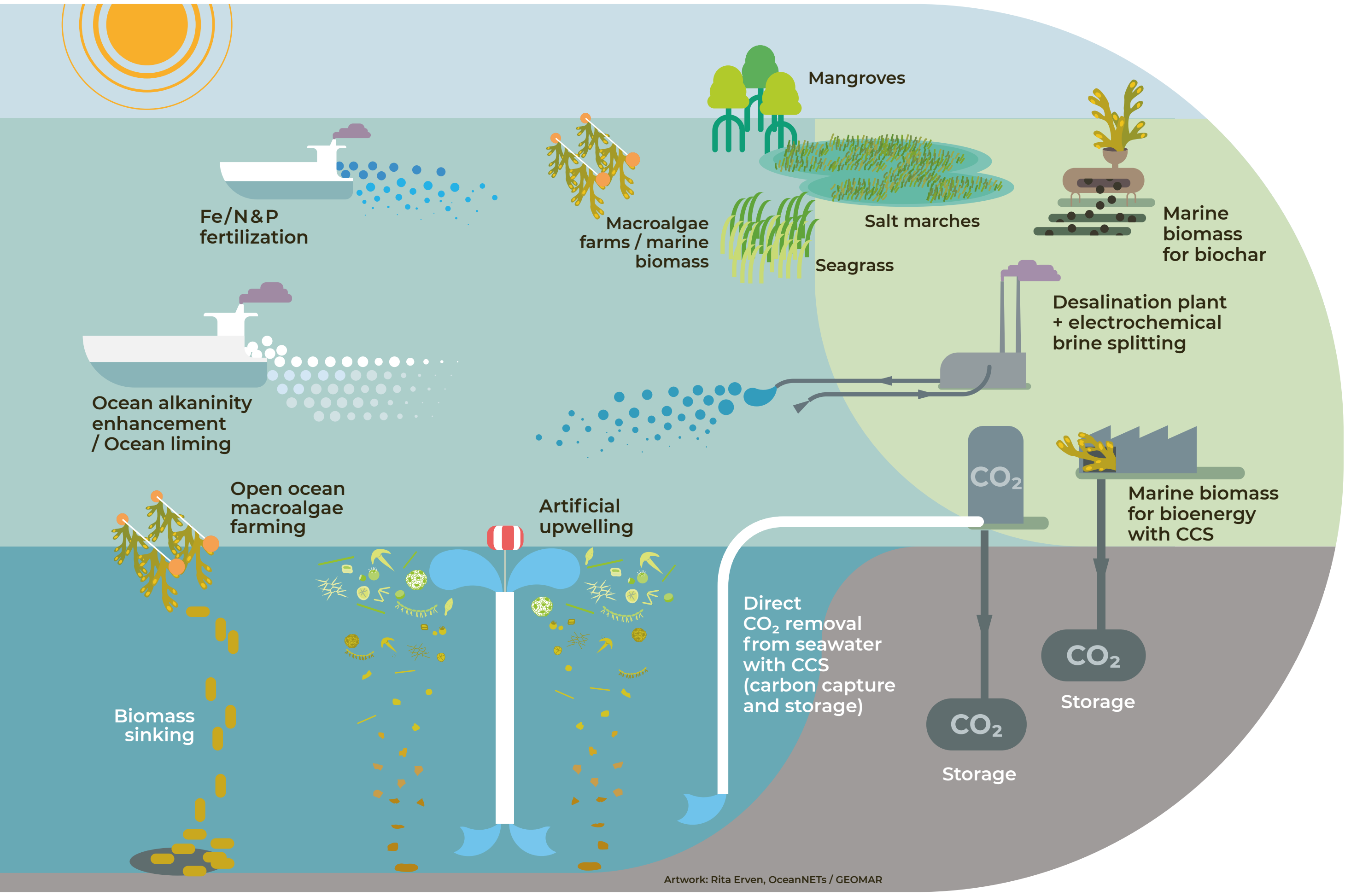

Figure 1: Overview of different approaches to marine CDR examined in the OceanNETs project.

Design by Rita Erven, OceanNETs / GEOMAR

OceanNETs' role in capacity building

With its transdisciplinary approach, OceanNETs began as a pioneering project in marine CDR research, with its first years representing an initial phase of capacity building that laid the foundation for interdisciplinary collaboration. Scientists from diverse fields learned to understand each other's terminology, methodologies, and perspectives on key questions. Over the past five years, research on marine CDR options has intensified, which has led to the emergence of related projects and numerous publications. One consequence of the early phase of capacity building was that some OceanNETs researchers have since been involved in other related EU projects such as RESCUE (https://rescue-climate.eu/), SEAO2-CDR (https://seao2-cdr.eu/), as well as in projects of the research mission CDRmare (https://cdrmare.de/en/), which has contributed to a more far-reaching synthesis beyond OceanNETs itself. A broadening of knowledge capacities on NETs in general has been achieved through establishing communication channels with those EU projects that focused on the land sector, NEGEM (https://www.negemproject.eu/) and LANDMARC (https://landmarkproject.eu/) respectively. A final clustering and consolidated exchange of outcomes between OceanNETs, NEGEM, and Landmark took place during the Brussels policy event in April 2024.

General achievements

OceanNETs has contributed to a better understanding of possible strategies for achieving the climate goals set out in the Paris Agreement. This includes insights into mutual influence of the United Nations' Sustainable Development Goals (SDG), in particular of SDG 13 (climate action) and SDG 14 (life below water). The realistic techno-economic scenarios of OAE, developed in OceanNETs, are linked to aspects of SDG 9 (innovation, industry and infrastructure). OceanNET's experimental studies covered elements of SDG 14 together with the potential impacts on fish development, which is relevant to SDG 2 on food security through fisheries. The legal and governance research of OceanNETs derived relevant and timely findings and policy recommendations that relate to Target 14.c of SDG 14.

DELIVERABLES
71

PUBLICATIONS
63

POLICY BRIEFS
4

Overall, OceanNETs has generated 71 deliverables (https://www.oceannets.eu/deliverables/) and has published 63 scientific papers (https://www.oceannets.eu/publications/) so far, including research input to the Guide to Best Practices in Ocean Alkalinity Enhancement Research (https://sp.copernicus.org/articles/2-oae2023/). Four policy briefs have been developed (https://www.oceannets.eu/downloads/) that i) recommend decision-makers to adopt a wider governance perspective to strengthen current regulatory mechanisms and a 'good governance' approach to navigate challenges related to marine CDR, ii) explain why OAE is amongst the most promising ONET approaches, and provide elaborated insights into realistic deployment scenarios for OAE based on iii) ocean liming and iv) electrochemical brine splitting in conjunction with the desalination of seawater.

PEOPLE SURVEYED
~12,000
IN 6 COUNTRIES

OceanNETs members contributed to the creation of a roadmap for planning and scoping multi-disciplinary research activities on CDR techniques in the ocean, which was an initiative of the Aspen Institute. This activity helped to devise and finalize A Code of Conduct for Marine Carbon Dioxide Removal Research, published in November 2023. Experiences and outcomes gathered in OceanNETs entered the section on ocean-based CDR in the Cross-sectoral perspectives chapter of the IPCC AR6 report (Babiker et al., 2022)

MAJOR STAKEHOLDER EVENTS
7

During the course of OceanNETs approximately 12,000 people were surveyed to examine the public perceptions of a portfolio of ONETs. Stakeholders were informed and consulted by OceanNETs colleagues, participating in two governance workshops, two stakeholder events on OAE, and two science-policy discussions in Brussels, with some attending

MESOCOSM EXPERIMENTS
2

multiple activities. Two OceanNETs experimental mesocosm studies were conducted to assess potential impacts of OAE on geochemistry and plankton dynamics, yielding first measurements of this kind. The provision of realistic future scenarios for OAE options is a significant cross-cutting synthesis result of OceanNETs, which currently represents a unique outcome. These scenarios were directly integrated into a series of simulations, using dynamic models that resolve processes from regional to Earth system scale.

Chronological overview of OceanNETs progress

The project began in July 2020 with an initial exchange of information about research activities and first results, which were carried out exclusively in a virtual setting. The two mesocosm studies, in Gran Canaria, Spain and in Bergen, Norway, were re-designed so that they could be conducted even under the difficult conditions of the COVID pandemic.

Major events with stakeholders, political decision-makers, and laypersons were well distributed during and after the pandemic. These workshops and surveys all happened before the final policy event at the Square Brussels Convention Centre on 18 April 2024. During this event, scientists from the projects NEGEM and LANDMARC, and OceanNETs jointly presented and discussed research findings about land-based and ocean-based CDR technologies across disciplines. For the OceanNETs Consortium, a project extension was agreed upon, especially to conclude the measurements and analyses of the samples from the experiments within the project time frame. The project officially ended on June 30, 2025.

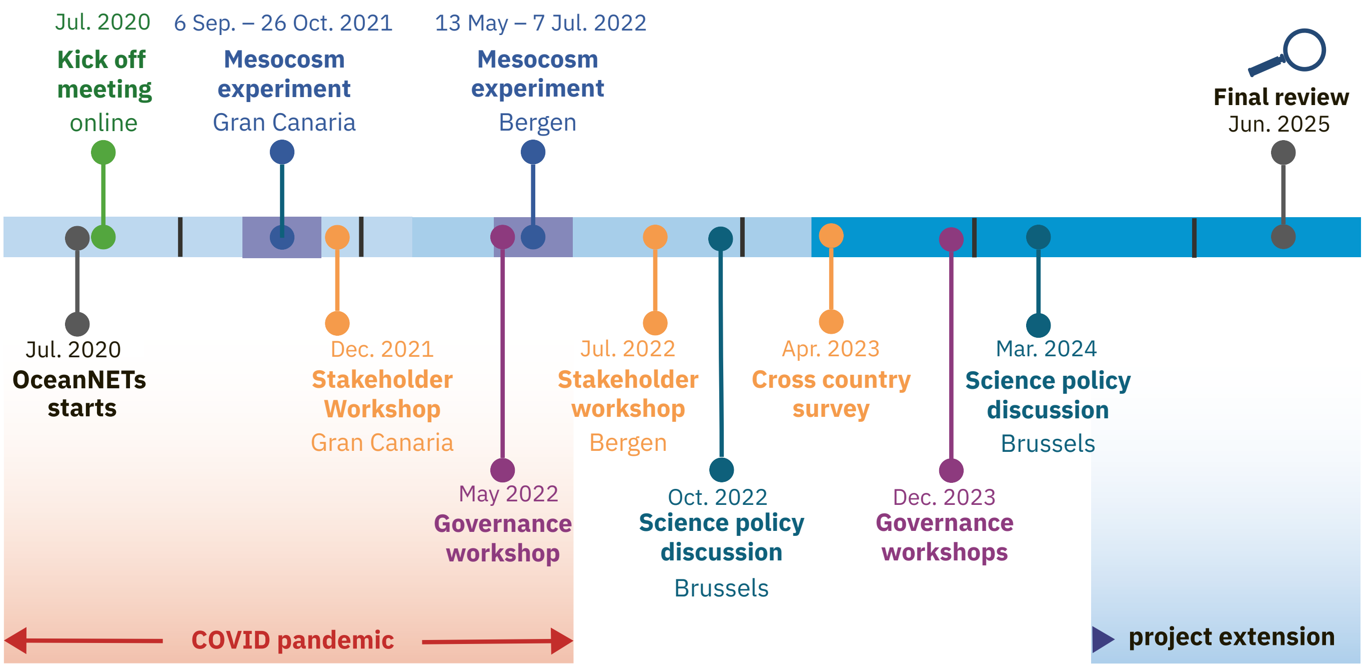

Figure 2: Chronological development of important events during the course of the OceanNET project

KEY MESSAGES

1 Syntheses of trans- and interdisciplinary research on ONETs always contain information of varying depth and scope.

With its integrative approach, OceanNETs was able to build a solid foundation for the exchange of information on research methodologies and results across a wider range of experts. An important takeaway was that elaborations in one research field can be so dependent on progress in other areas that a complete end-to-end synthesis will not necessarily be achievable at all times. These mutual interdependencies, between technical, ecological, social, and political levels of knowledge about ONET options, underscore the iterative nature of an integrative approach.

An explicit statement on the mutual dependencies of information appears necessary, in particular to avoid excessive expectations regarding the comparability of different ONETs, which may affect policy decisions. It should be pointed out to stakeholders and the public that syntheses, like cross-comparisons between ONET pathways, will inevitably reflect findings from individual disciplines of varying depth and scope.

2 Credible assessments of the scalability of an ONET require information about its social and techno-economic constraints.

Credible evaluations of the feasibility and scalability of ONETs require detailed information on resource availability and existing and expandable infrastructure. So far, economic constraints of ONETs have been derived using techno-economic and socio-economic models, Integrated Assessment Models, as well as policy evaluations. Examining the still largely unassessed macro-economic price effects of resources required for ONETs would offer additional insights into their socio-economic impacts and trade-offs. However, by placing greater emphasis on ocean alkalinity enhancement (OAE), the project was able to conduct a more systematic assessment of realistic deployment pathways and potential impacts, adding substantial value for synthesis and supporting effective public engagement.

Assessments under real-world conditions are particularly valuable. When assessing the feasibility and scalability of ONETs, social fairness and the coastal economy should be addressed, but to ensure credible economic assessments, only induced or dynamic economic effects should be accounted for. Based on the experiences gathered during OceanNETs, it is recommended to carefully consider public acceptability, existing regulatory frameworks, and governance processes, as this societal and governance perspective is essential besides natural science and engineering insights to guide how legal frameworks could be updated and clarify how political decisions and socio-economic incentives could promote specific ONET options.

3 Forward-looking climate policies must urgently create incentives for the timely implementation of ONETs.

Achieving net-zero emissions will require a portfolio of ONETs alongside land-based NET approaches. Individual ONETs typically have CDR capacities ranging from 0.05 to 4 $GtCO_2$ yr^{-1}, with higher removal rates (10 – 16 $GtCO_2$ yr^{-1}) possible only during the first decade of implementation, when CO_2 emissions remain high. ONETs therefore offer only limited contributions relative to current anthropogenic CO_2 emissions (40.6 ± 3.2 $GtCO_2$ in 2023), making rapid and substantial emissions reductions indispensable. ONETs have the potential to play a significant role in future climate policies, but success depends on early and strategic investments, robust monitoring systems, and international cooperation.

Given the long lead times for effective marine CDR options, policies must incentivize development in the near term, alongside robust economic cost estimates and further evaluations of potential environmental and socio-economic co-benefits, trade-offs and risks. Because of the urgent near-term horizon, a forward-looking climate policy should build on realistically achievable deployment scenarios that include energy projections and supply chain constraints, while continuing to integrate existing infrastructure, such as operating cement- and desalination plants considered for the life cyle assessments (LCAs) of OAE, or in case of blue carbon the seaweed industry for macroalgae farming and harvesting.

4 Multi-level frameworks are needed that facilitate the alignment of local efforts with international regulations for ONETs.

The current conditions for governance of marine CDR do not yet adequately address the complexity of ONETs. The existing international, national, and regional regulations, many of which overlap and are distributed among various regulatory frameworks, create an incoherent basis for governance. Decision-making on marine CDR is complicated by potential trade-offs and risks, including ethical and justice concerns. These issues must guide research and ensure that future ONET deployments are pursued responsibly, transparently, and with precaution. Effective governance of ONETs requires comprehensive, forward-looking, multi-level frameworks. Such multi-level frameworks should operate along the objectives of 'good' environmental governance in terms of being effective, equitable, responsive and robust in such a way as to remain flexible and adaptive on a regional level. This should enable strategies tailored to local conditions for public acceptability, while also addressing economic and environmental factors, and remaining aligned with climate, biodiversity, and sustainability goals.

Further coordination of ONETs within the ocean-climate nexus of environmental governance (London Protocol, CBD, Paris Agreement Art. 6.4) is recommended, along with a practical regulatory framework to enable local-scale deployment. This should give priority to OAE and blue carbon applications. Against this background, prerequisites for the regulation of local pilot studies would be helpful and should be developed in a timely manner.

5 Exchange of complementary information between disciplines and stakeholders can be best synchronized by focusing on specific sites of ONET deployment.

Practical case studies and field work are essential for a best possible assessment of ONETs, while taking into account site-specific environmental, social and political conditions. By focusing on site-specific operational requirements, the exchange of complementary information across disciplines and stakeholders can be better synchronized. Particularly, fundamental difficulties in practice as well as obligations to and possible solutions for public engagement can then be more clearly disclosed. Site-specific studies would also serve to stress-test existing governance frameworks, uncover underlying attitudes toward climate action, and identify those institutional actors (governmental, corporate, or non-profit) that are best positioned to manage and control the deployment of ONETs.

Studies with regional focus are recommended for understanding the real costs, co-benefits and risks of ONETs. They could help shape public confidence in the effectiveness and safety of ONETs. The evolving regulatory criteria for site-specific experimental ONET studies could make an important contribution to multi-level governance frameworks. The guiding principles for such studies could be continuously improved, covering the planning and scope of the research and the termination and decommissioning of an ONET.

6 Opportunities for the utilization and further expansion of existing infrastructure are promising for two ONETs.

Macroalgal farming and harvesting, as a blue carbon strategy, and OAE are two ONET options that can directly benefit from leveraging existing infrastructure. Blue carbon has a comparatively small CDR potential but can facilitate monitoring, reporting, and verification (MRV). If biomass sinking is avoided, blue carbon enjoys high public acceptability and offers potential ecological and socio-economic co-benefits. OAE scenarios devised in OceanNETs demonstrate substantial CDR potential under realistic conditions, for example by integrating ocean liming with cement industry processes, where carbon capture and storage should then be employed and energy requirements reduced. Despite relatively minor side effects compared to other ONETs such as artificial upwelling or ocean fertilization, the public acceptability of OAE remains low. It also faces greater MRV complexity and involves certain biological and geochemical uncertainties.

Advancing research through modelling and experimental studies on these two ONET options is therefore essential. Without such progress, their deployment may not be realized in the near future at the scales needed. For OAE, achieving the necessary scale is crucial for delivering substantial CDR. In the case of macroalgal farming and harvesting, this ONET option can support ecosystem-based climate change adaptation and contribute to carbon-neutral food production, rather than serving as an effective CDR strategy for climate mitigation.

7 Efficiency estimates of OAE are sensitive to emission pathways, the models' spatial resolution, and the conditions for precipitation of calcium carbonate.

The results from model simulations of ocean liming (OL), which is one feasible OAE option, reveal large variations in the efficiency of CO_2 sequestered per unit of alkalinity added to the upper ocean layer. The simulated efficiency of OAE varies in time and space, approximately between 0.3 and 0.8. It is sensitive to the projected CO_2 emission pathways, revealing highest efficiencies only for high emission scenarios. Simulated OAE efficiencies are generally lower in models that have a higher spatial resolution of the ocean than resolved by the Earth System Models (ESMs). OceanNETs experimental and modelling study document how the efficiency of OAE can become zero or even negative on short term, in cases when secondary precipitation of calcium carbonate ($CaCO_3$) occurs.

The sensitivities of the efficiency of OAE documented by the OceanNETs simulations point out how important it is to interlink emission scenarios from Integrated Assessment Model applications with ESM simulations. If biases in alkalinity and dissolved inorganic carbon, as documented in OceanNETs, are reduced, uncertainties in estimates of the efficiency of OAE can be further reduced in ESM applications. The potential case of $CaCO_3$ precipitation, and its effect on the efficiency of OAE, suggests that critical conditions of precipitation should be further investigated experimentally and incorporated into regional, basin, and Earth-system models.

8 Impacts and the ecological safety of OAE without prior CO_2 equilibration are strongly context-dependent.

The experimental studies within OceanNETs focused exclusively on the biological and geochemical responses to OAE. Exponential phytoplankton growth under nutrient-replete conditions may exhibit more distinctive and easier-to-detect adverse responses compared to nutrient-poor conditions. Consequently, the impact of OAE varies depending on whether it occurs before or after the development of phytoplankton blooms. The addition of alkalinity prior to a bloom can delay bloom development, as less CO_2 is available for algal growth. These time delays also affect zooplankton food availability, although they appear to have only minor impacts on overall zooplankton development. Similarly, OceanNETs results suggest that fish larvae and juveniles may remain viable under OAE. However, uncertainties remain regarding compositional changes in the plankton community following the deployment of different minerals for OAE, such as calcium-based minerals in case of OL or silicate-based olivine.

Favorable regions and periods for OAE, where impacts on plankton are minimal, are typically associated with nutrient depletion and low primary production rates, as observed in oligotrophic regions. Experimental studies should examine variations in nutritional status, which could potentially exacerbate the ecological impacts of OAE. Research on the effects of OAE on microbial loop dynamics and plankton community composition is essential for a better understanding of its ecological consequences. Additional experiments are also needed to identify the critical conditions that may trigger precipitation of $CaCO_3$.

9 There are tangible ways to minimize the environmental impact of OAE and maximize its economic efficiency.

The results of the LCAs conducted in OceanNETs not only provided feasible OAE options, but also revealed meaningful additional valorization pathways, particularly in the case of OL.

For OL the CO_2 emissions during the calcination process could be minimized through the use of low-carbon technologies such as solar calciners and the integration of CO_2 capture and storage (CCS). In addition to these valorization strategies, the recovery of low-grade heat, i.e., the heat energy released during the hydration of calcium oxide and the utilization of high-purity CO_2 released during limestone decomposition offer further opportunities to improve the environmental performance of OL. These measures could yield emission credits and promote the overall environmental performance of OL.

Investigations should focus on optimizing the calcination process and creating more detailed, region-specific deployment scenarios for OAE, considering projections of energy sources and supply chain limits. The associated LCAs should then elaborate on ecosystem impacts as well as co-benefits such as partial mitigation of ocean acidification, while incorporating complementary information from ESM and plankton ecosystem model simulations.

Research approaches and key findings from OceanNETs

(A) Society and ONETs

De Pryck and Boettcher (2024) clarified that the implementation of ONETs, as a contribution to achieving climate targets, depends as much on social and political considerations as on technical and scientific factors. According to their study, the current high level of attention to marine CDR approaches is driven by modern socio-technical configurations, coalitions and narratives rather than technological breakthroughs. In that sense, the social dimension was examined in OceanNETs, using various scientific approaches and analytical perspectives to elucidate current and potential future economic, political, social, and legal feasibility and desirability of ONETs.

Public perception

The public perceptions of a broad range of ONETs approaches were examined, extending beyond the geographical scope and methods addressed in past studies, integrating insights from both qualitative and quantitative studies (Veland and Merk, 2021, **D3.3**; Andersen et al., 2022, **D3.4**; Merk et al., 2023, **D3.5**). After an initial review of the literature (Bertram and Merk, 2020), seven exploratory focus groups (FG) with laypersons in Germany and Norway were conducted. These were two-hour moderated online sessions that followed a question guide and were supported by OceanNETs' infographics for the carbon cycle, the magnitude of the carbon sinks, ocean fertilization, artificial upwelling, ocean liming, and coastal ecosystem restoration (Merk, 2021, **D3.1**; Veland, 2021, **D3.2**). The transcribed discussions were analysed in Veland and Merk (2021, **D3.3**).

Often there are calls for public participation and deliberation on CDR methods. Two deliberative surveys (DS) were conducted on net-zero climate policy and CDR research and deployment in Norway (N=89). This study focused on OL as a form of OAE, as well as macroalgae cultivation, either with bioenergy with carbon capture and storage (BECCS) or with biomass sinking, as marine CDR options, and compared them to their land-based counterparts, including BECCS with terrestrial biomass and enhanced rock weathering. The experimental design allows the comparison of participants' perceptions before and after the four-hour deliberation, with perceptions elicited via a survey. Furthermore, the survey responses can be compared with those of a group that deliberated an unrelated topic. This was complemented by the analysis of the discussions in the groups during the deliberation, the results of which are presented in Andersen et al. (2022, **D3.4**).

The final round of data collection extended the geographical focus and the opportunities to generalize the findings. The comparative cross-country survey (CS) experiment looked at the perceptions of climate policy, OAE, macroalgae cultivation coupled with BECCS or biomass sinking in Canada, China, France, Germany, Norway, and Taiwan with 2000 observations per country (Merk et al., 2023, **D3.5**). The combination of qualitative and experimental quantitative methods allows for the contextualisation of ONETs in the experiences of previous novel interventions, climate policy and national experiences, as well as for the comparison between countries and methods.

KEY FINDINGS

PUBLIC PERCEPTION

Public acceptability is widely recognized as a key barrier to the application of ONETs (GESAMP 2019; IPCC, 2022a; Rickels et al., 2019). Table 1 summarizes the publics' associations with, concerns about and levels of support for the eight NETs studied in OceanNETs. In the focus groups and the deliberations laypersons often associated the ONETs methods with issues and debates they are already familiar with. The level of participants' awareness about the methods, mirrors their novelty: Self-reported familiarity with CDR approaches is low especially in Western countries surveyed, where a majority (55–84 %) report never having heard of these approaches. Whereas in China and Taiwan, the majority (56–75 %) stated that they had heard about these methods before. In the CS, this is also reflected in a high share of respondents answering "do not know" or "no opinion" when asked about specific CDR methods (Merk et al., 2023, **D3.5**). In addition, laypersons are mostly unfamiliar with natural processes in the ocean that would be enhanced by these ONETs and ocean-based removal is often perceived as uncontrollable (Veland & Merk, 2021, **D3.3**; Merk et al., 2023, **D3.5**). This could also explain the greater concern about marine than about terrestrial CDR approaches found in the deliberative survey (Andersen et al., 2022, **D3.4**).

Table 1: Summary of the publics' associations, concerns and levels of support, differentiated by the eight NETs (six ONETs and two land-based NETs). The data are based on the outcomes of the exploratory focus groups (FG), the deliberative surveys (DS), and the comparative cross-country survey (CS).

Negative Emission Technology (NET)	Data	Associations	Concerns	Public support
Artificial upwelling (Ocean-based NET)	FG	Offshore wind energy	Feasibility	Low
Blue carbon enhancement (Ocean-based NET)	FG	Natural process	Invasive species, human interventions going wrong	High
Ocean fertilization (Ocean-based NET)	DS	Marine pollution	Feasibility, controllability	Low
Ocean alkalinityeEnhancement (Ocean-based NET)	FG DS & CS	Marine pollution, freshwater liming, not environmentally friendly nor feasible	Additionality, mining, energy footprint, controllability	Low Low/medium in China
Enhanced weathering (Land-based NET)	DS	Fertilization	Mining, energy footprint	Low/medium
Macroalgae farming (Ocean-based NET)	DS CS	Aquaculture	Monoculture, pollution	
with biomass sinking		Waste dumping at sea; in CS: risky, uncontrollable	Controllability, impermanence of storage	Low in Western countries; Low/medium in Asian countries
with Carbon Capture and Storage (CCS)		CCS as climate solution; in CS: innovative	Additionality related to CCS	Low/Medium in Western countries; Medium in Asian countries
Terrestrial bioenergy with CCS (BECCS) (Land-based NET)	DS	Agriculture, CCS as climate solution	Land-use, food production	Low/Medium

PUBLIC PERCEPTION

Notably, we find an effect of deliberation on the share of "do not know"/"no opinion"-responses in the DS. Their share dropped significantly between the pre- and the post-survey, where in the meantime participants were informed about and were provided the opportunity to deliberate CDR approaches and net-zero policy. At the same time, the general assessments of the methods changed only slightly. This means deliberation did not lead participants to more positive or more negative assessments but increased their capacity to assess the methods (Andersen et al., 2022, **D3.4**). The discussions in the focus groups and deliberation illustrate that participants found it hard to engage with the idea of removing CO_2 and the methods. They tended to discuss the importance of reducing emissions and changing consumption patterns, instead of the need to remove CO_2 from the atmosphere in addition to drastically reducing emissions to reach climate goals. However, no treatment effect was found in the CS of showing information on CDR methods on support for concrete climate policies, such as the expansion of renewable energies or carbon taxes (Merk et al., 2023, **D3.5**).

Despite the skepticism towards specific CDR approaches in our studies, we found clear support for continued research and innovation on ONETs. Most participants also perceived the information available for methods as too limited and asked for more information to form an opinion (Andersen et al., 2022, **D3.4**; Veland & Merk, 2021, **D3.3**).

Governance

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The ocean and society are inherently linked, both directly (e.g., food webs) and indirectly (i.e., ecosystem services, e.g., food provision). Just as the ocean is heterogeneous in its geochemical and biological composition, the ocean also varies in how it is socially constructed, culturally perceived and economically valued by society. Different socio-cultural, ecological, political and economic dimensions have historically influenced the development of multilateral environmental governance, and these same factors are increasingly relevant to the governance of ONETs. Given the ocean's transboundary nature, its vital role in sustaining ecosystem services, and the diverse and context-dependent impacts of proposed ONETs, a comprehensive, adaptive, and pluralistic governance approach is essential for the responsible development and oversight of marine CDR.

The future of ONEts will invariably depend upon existing agreements and disagreements over the proper use and governance of the oceans as well as live questions regarding the politics and justice implications of a broader family of climate interventions (CDR, CCS, solar radiation management). A signal contribution of the OceanNETs consortium is its explicit interdisciplinary design, which departs from most previous state-of-the-art studies of climate intervention that have prioritized natural scientific and technical assessments. By including a variety of social scientific approaches, it has meaningfully advanced scholarly understanding of the sociopolitical complexity of ONETs and climate intervention more broadly.

International, regional, and national regulations, many of which overlap in scope, leave gaps across jurisdictions and sectors, or lack coherence, complicate the governance of marine CDR. To elucidate the gaps and challenges relating to the regulation and management of ONET deployment, and derive recommendation for policy- and decision-making, document analysis, expert elicitations and stakeholder dialogues were combined in order to gain a better understanding of the relevant regulations, institutions, processes and actors. An online questionnaire was developed for distribution within the OceanNETs consortium to identify potential effects of ONETs on the ocean's condition and related coastal and marine

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ecosystem services, the results of which formed the basis for a subsequent comprehensive literature review of eight different ONETs considered in the OceanNETs project Röschel and Neumann, 2023; (Röschel and Neumann, 2024a, **D2.5**). The findings supported the identification of relevant governance frameworks for ONETs and the meaningful categorization into direct (explicit), indirect and implicit governance, disentangling the complex multilateral governance framework or 'regime complex' for the ocean in relation to ONETs (Röschel and Neumann, 2023). An online workshop with experts supported the identification of key challenges to comprehensive ONET governance (e.g., decision-making under urgency and deep uncertainty) early on in the project (Röschel and Neumann, 2022, **D2.3**). An in-person scenario workshop with diverse experts reflected on the identified current and potential future challenges of ONET governance (Röschel and Neumann, 2023, **D2.4**). The workshop discussions also supported the development of 'good governance principles' for ONETs that were distributed to decision-makers via a policy brief (Röschel and Neumann, 2024b, **D2.6**).

Furthermore, the consortium deployed historical and anthropological techniques to investigate the framing of ONETs as at once "necessary" and "experimental" through comparative studies of the relationship between science and society in the US, Germany, and Australia. This work demonstrates that the considerable momentum behind ONETs builds on highly contingent but ingrained assumptions, practices, ideological commitments, and geopolitical hierarchies that together stabilize a vision of the oceans as an industrial frontier and solution space for the climate (Bright and Schäfer, 2024, **D2.1**). It shows that difficulties engaging local communities are a structural feature of CDR research, which the "portfolio" approach responds to but cannot resolve in practice.

A more specific evaluation of the social impacts of applying OAE as ONETs was worked out by Nawaz et al. (2023), who could engage local industries and non-governmental organisations (NGOs) at the sites where the OAE mesocosm studies were conducted, in Bergen, Norway, and Gran Canaria, Spain respectively (Lezaun, 2021, **D7.1**; Lezaun et al., 2022, **D7.2**). Their assessment also includes a participatory evaluation of OAE LCA with relevant industries (e.g., lime production, desalination, as well as interviews with experts in OAE research and development, including academics and start-up researchers. An initial consultation held on December 13, 2021 (Lezaun et al., 2021, **D6.3**) brought together twelve stakeholders from industry, government, and academia to discuss the LCA of carbon-negative production of lime and, to some extent, of cement. Key topics included CCS, CO_2 removal financing, regulatory frameworks, scalability, and public acceptability. The session concluded with plans for follow-up consultations and interviews, underscoring the importance of stakeholder input in assessing the social impacts of ONET deployment (Nawaz et al., 2023).

KEY FINDINGS

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Large-scale deployment of ONETs is considered as a potential part of the pathway towards reaching net-zero carbon emissions by 2050, in line with the ambitions set by the Paris Agreement of limiting global warming 'well below 2°C, preferably 1.5°C' (UNFCCC-Art. 2(a), 2015). The direct and intentional impact of ONETs (i.e., to change the physical, biochemical or biological condition of the ocean for increased uptake and sequestration of atmospheric CO_2) aims to enhance the ocean's role in achieving global climate goals. In addition to the intended impact of ONETs, the interactions between ONETs and the ocean may create unintentional impacts, either directly by inducing further changes in the ocean's condition alongside the intended impact (e.g., an increase in trace metals) or indirectly impacting related ecosystem services

Table 2: Classification of four distinguished ONET's impacts on the ocean and the description of the respective classes. The direct impact is assessed as a change in ocean conditions via Essential Ocean Variables (EOVs). Indirect impacts are evaluated as changes in marine and coastal ecosystem services.

Impact of ONET on ocean	Description
Direct intentional impact	All ONETs deployed for CDR intend to change the physical, biochemical, or biological/ecosystem condition of the ocean for the increased uptake and sequestration of atmospheric CO_2
Potential direct unintentional impact	Dependent on the ONET's approach to enabling an intentional change in ocean condition, unintentional side effects can potentially occur that further impact the physical, geochemical, or biological condition of the ocean, e. g., increase in trace metal concentration, change in nutrient availability, shifts in species composition.
Indirect intentional impact	The indirect intentional impact of all ONETs deployed for CDR is climate regulation. A change in the ocean's condition to increase uptake of CO_2 is thus intended to strengthen the role of the ocean in climate regulation.
Potential indirect unintentional impact	The identified direct unintentional changes in ocean condition potentially have an indirect unintentional impact on coastal and marine ecosystem services, e. g., food provision or nutrient cycling. These changes in ecosystem services and their supply could either offer co-benefits or be viewed as trade-offs to the intentional impacts of ONETs.

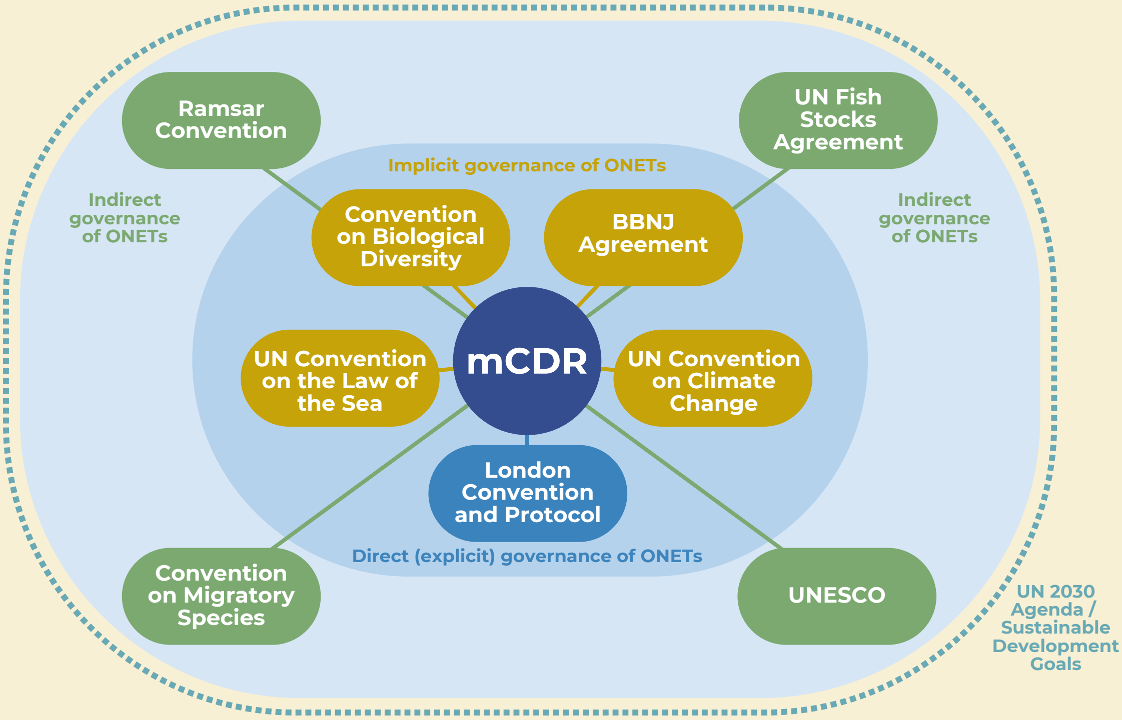

Figure 3: Extended governance framework relevant to marine CDR, according to Röschel and Neumann (2023).

(e.g., enhanced fish stocks) (see Table 2; Röschel and Neumann, 2023). Unintended impacts can be of positive or negative nature to the environment and society, and can be classified as hindering or supportive of a wide range of global governance frameworks or policy goals. Decision-makers may benefit from adopting a broader perspective for understanding the wider implication of ONET deployment for the environmental governance regime.

In Figure 3 and Table 3 the relevant environmental governance frameworks and their relation to ONETs are presented. The London Convention and Protocol[1] explicitly

1 *The 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention) and the 1996 Protocol on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Protocol) are generally referred to as a treaty complex (LC/LP).*

Table 3: Overview of the relevance of eight ONETs across the international environmental governance regime.

Governance Frameworks	Ocean alkalinity enhancement	Ocean fertilization	Direct CO_2 removal	Artificial up-welling / down-welling	Blue carbon management	Biomass for biochar / bioenergy	Biomass dumping
London Convention and Protocol (LC/LP)	indirect relevance	explicit (direct) relevance	indirect relevance	indirect relevance	indirect relevance	unresolved	explicit (direct) relevance
Convention on Biological Diversity (CBD)	implicit relevance	implicit relevance	implicit relevance	implicit relevance	implicit relevance	implicit relevance	implicit relevance
United Nations Convention on the Law of the Sea (UNCLOS)	implicit relevance	implicit relevance	implicit relevance	implicit relevance	implicit relevance	implicit relevance	implicit relevance
United Nations Framework Convention on Climate Change (UNFCCC)	implicit relevance	implicit relevance	implicit relevance	implicit relevance	implicit relevance	implicit relevance	implicit relevance
BBNJ Agreement	implicit relevance	implicit relevance	implicit relevance	implicit relevance	implicit relevance	implicit relevance	implicit relevance
2030 Agenda for Sustainable Development	implicit relevance	implicit relevance	implicit relevance	implicit relevance	implicit relevance	implicit relevance	implicit relevance
Ramsar Convention on Wetlands (Ramsar Convention)	unresolved	unresolved	unresolved	unresolved	indirect relevance	unresolved	unresolved
Convention on the Conservation of Migratory Species of Wild Animals (CMS)	indirect relevance	indirect relevance	indirect relevance	indirect relevance	unresolved	unresolved	indirect relevance
Convention for the Protection of the World Cultural and Natural Heritage (UNESCO)	indirect relevance	indirect relevance	indirect relevance	indirect relevance	indirect relevance	unresolved	indirect relevance
UN Fish Stocks Agreement	indirect relevance	indirect relevance	indirect relevance	indirect relevance	indirect relevance	indirect relevance	indirect relevance

explicit (direct) relevance · implicit relevance · indirect relevance · unresolved

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regulate ONETs (i.e., currently limited to ocean fertilization) as 'geoengineering' as the primary framework for protecting the ocean from pollution caused by dumping or disposal of waste or other matter. In addition, ONETs are implicitly governed by environmental governance frameworks that are relevant to the direct impacts of ONET activities on the ocean condition, such as the Convention on Biological Diversity (CBD), which has the objective to conserve biological diversity and promote sustainable use and the fair and equitable sharing of related benefits to society. A range of governance frameworks with relevance to unintentional impacts of ONETs on ecosystem services are included in the extended governance framework (i.e., indirect governance of ONETs), such as the UN Fish Stocks Agreement (see also Röschel and Neumann, 2023). For comprehensive regulation and management of ONETs, the proposed extended governance framework should be taken into consideration by decision-makers in order to maximise coherence and co-benefits across different policy goals (i.e., multilateral environmental agreements). Integration of a 'good governance' approach, in combination with this wider perspective can help navigate the many challenges and complexities related to governance of ONETs, such as remaining deep uncertainties with regards to possible unintended side effects and the potential for urgency in decision-making in the future, and can serve as a way to overcome policy lock-ins or paralysis. Such a good governance approach should be guided by a set of principles for

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ensuring, e.g., transparency, accountability and justice (see **Röschel and Neumann, 2024a**, **D2.5**; 2024b, **D2.6**). Good governance would include e.g., foresight in relation to the wide range of emerging ONET approaches (not limited to ocean fertilization), coordination between relevant regimes across all levels of governance and consideration of all relevant stakeholder groups and their interests and views in decision-making processes (see **Röschel and Neumann, 2024a**, **D2.5**, for a list of principles of good governance of marine CDR).

Lezaun (2021) emphasized early in the project the local, and thus site-specific, nature of the suggested marine CDR strategies. The crucial albeit complex role of local governance of different ONETs, e.g. in coastal communities, have been further elucidated in **Nawaz et al.** (2023). Their findings clarify that trade-offs between local and global interests pose ethical challenges. It is emphasized that approaches like OAE must align with local regulatory frameworks, public acceptability, and stakeholder engagement while addressing ecological, social, and economic challenges. Research on OAE draws on expertise in ocean alkalinity and pH dynamics. While the public may be familiar with the carbonate system from seawater aquariums, these small-scale experiences provide only limited insight into the potential ecological and societal consequences of large-scale OAE. Even if a site is considered biogeochemically optimal for OAE, a community's objection to a local application, due to significant livelihood risks, must be treated as a primary concern. Valuable and conclusive insights into governance can thus only be achieved through an iterative process in which scientific studies clarify the potential environmental impacts of OAE, and the regulatory framework is adjusted accordingly at the local level.

Socio economics

SOCIO ECONOMICS

To properly assess ONETs within climate policy, it is important to understand their operational costs, possible side effects and social impacts, interactions with other mitigation measures, macro-economic effects induced by large changes in some sectors, and their potential contribution to climate change mitigation. With the exception of macro-economic effects, major knowledge gaps were addressed through analyses of accounting methods (**Paschen et al., 2023**, **D1.1**; **Rickels et al., 2023**, **D1.2**),refinement of cost estimates via expert consultations, improvements to integrated assessment models (IAMs), applications of general-equilibrium models, and investigations into the market development of ocean-based NET startups.

The various ocean-based NETs do not only have different economic prospects in terms of operational cost, but also in terms of the permanence of storage and side-effects and co-benefits involved. Accordingly, depending on the climate policy framework and in turn the applied economic assessment approach, different prospects of ocean-based NETs become relevant. While for example from a global planner integrated assessment perspective, non-permanence of carbon storage is less of a concern, it is a critical obstacle for decentralized deployment. Accordingly, different carbon accounting methods and approaches were assessed to deal with non-permanent carbon storage. Accurate carbon accounting was shown to be essential for comparing ocean-based NETs with other mitigation strategies. Furthermore, proposals were developed for integrating blue carbon projects into EU climate policy frameworks, alongside a MRV concept tailored to the unique uncertainties of ocean-based approaches. Operational cost estimates were improved to better understand the economic viability of these technologies, revealing that, while large-scale deployment ultimately depends on cost and attainable total volume, early exploration of alternative approaches relies more on regulatory recognition and coherent innovation strategies for ONETs.

Refinements to economic models enabled more robust policy recommendations by incorporating regional and environmental factors. Scenario tools and expert workshops supported assessments of deployment strategies, particularly for ocean alkalinity enhancement and macroalgae cultivation. Market trends were tracked to ensure research remained aligned with industry developments, highlighting how policy incentives like the U.S. Inflation Reduction Act are shaping the sector. Ultimately, economic assessment was emphasized as critical for evaluating the feasibility, risks, and climate policy relevance of ocean-based NETs, providing essential insights for researchers, stakeholders, and decision-makers.

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The currently prevailing view on the value chain of ocean liming (OL) primarily comprises the lime industry (including quarrying), shipping, ship building, as well as product and port logistics, which are all typically established industries. Yet the CO_2-neutral generation of electricity and heat, and in particular the CCS from the calcination process, are segments that have not yet been established. The scenario exercises of van Kooten et al. (2023, D1.4) indicate that OL could abate between 0.5 and 1.1 Gt of CO_2 annually by 2050 – 2060, with costs that, at least initially (before 2040), are projected to exceed EU ETS carbon prices (**Figure 4**), but may become competitive in the longer term. Yet, continued learning effects after 2060 may further reduce the unit-costs by 2070. However, while unit costs play a role in large-scale deployment, early-stage adoption is more dependent on regulatory approval, particularly under frameworks like the London Protocol. Once officially recognized, investment in ocean-based NETs is expected to increase. Broad agreement on the spatial and logistical organization of ocean liming, including fleet characteristics, will be essential for its large-scale deployment. Financial mechanisms such as tradable carbon removal credits and resilience bonds could enhance feasibility by supporting both carbon sequestration and adaptation functions, such as coastal protection. OceanNETs has developed a deployment scenario tool which allows the community to test how different assumptions affect the cost development of OAE.

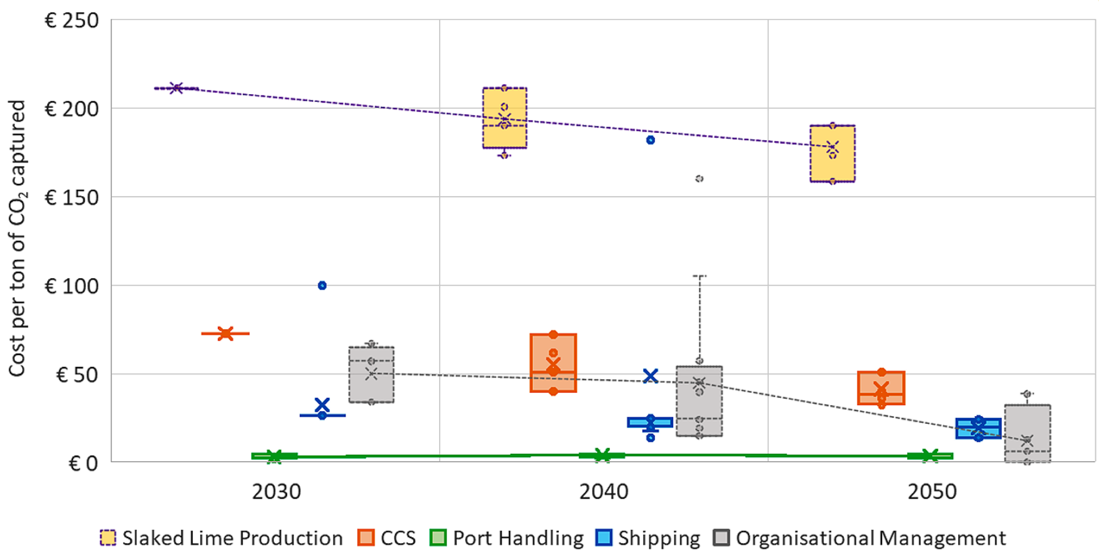

Figure 4: Cost breakdown of ocean liming based on scenario outcomes, according to van Kooten et al. (2023, D1.4). The crosses represent the average per production step per decade. The unit cost of CCS and lime production were rescaled to the cost per ton of CO_2 by a factor 1.321. For shipping, the upper outliers cause the averages to be above the 75th percentile (outside the boxes).

SOCIO ECONOMICS

Considerable regional disparities exist between CDR supply and demand, which provides valuable insights into the optimal integration of CDR into climate policy. Near-term demand for CDR is primarily driven by fragmented, inefficient climate policies. In a scenario with full international emissions trading, emissions reductions would still satisfy this demand and substitute for early CDR deployment. However, given the reservations against international emissions trading, considerable CDR demand will already arise in regions with ambitious climate targets and high abatement costs, such as Canada, Japan, UK, and the European Union in the year 2030. Marine CDR methods like macroalgae cultivation and harvest could provide a small, but relevant contribution to meeting this demand (Siebert et al., 2025). However, given the lead time required to provide reasonable carbon sequestration efficiencies, anticipatory climate policy would start incentivizing the scale-up of such methods already now and banking early removal credits for later.

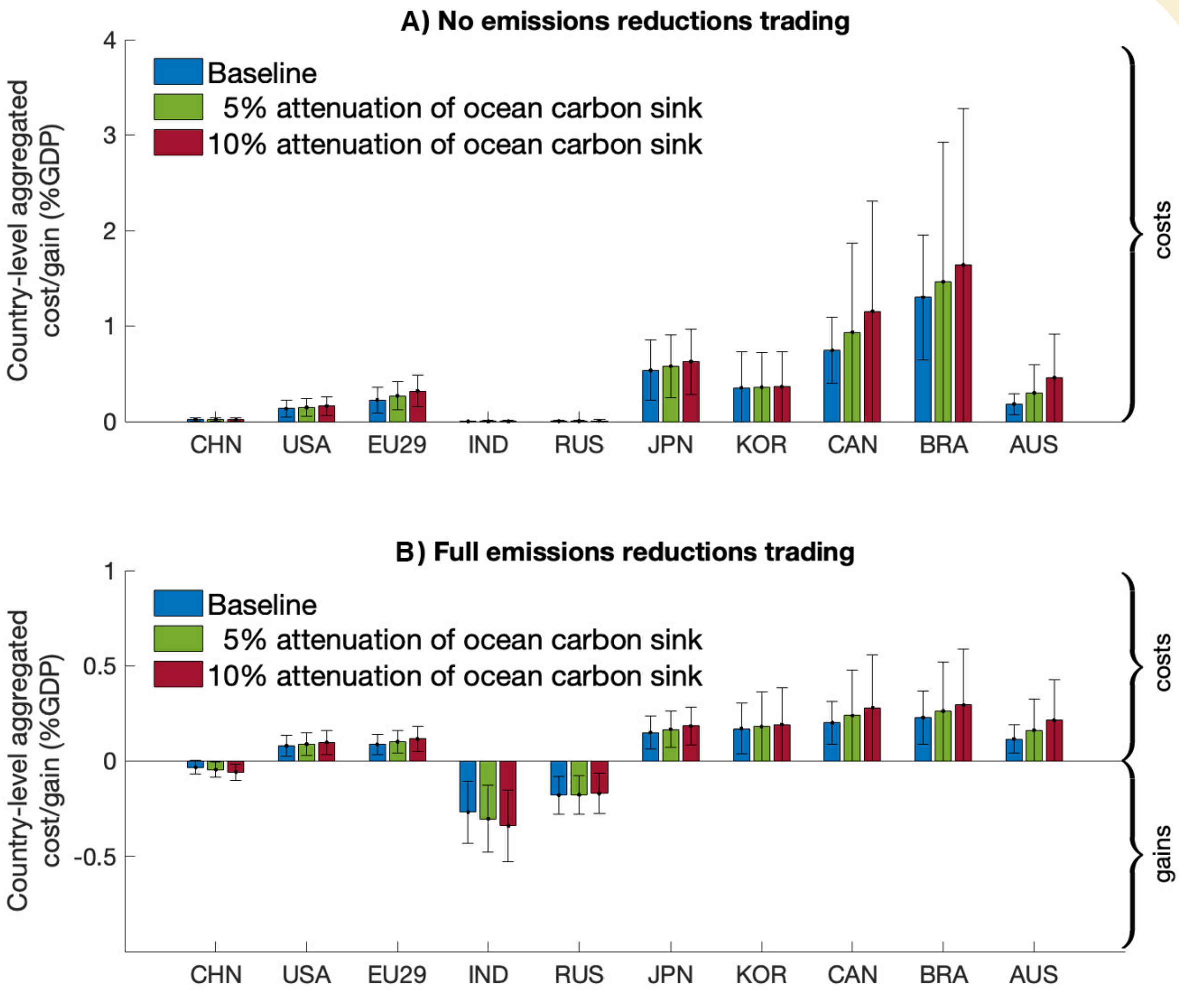

Figure 5: Cost implications of the weakening of the ocean carbon sink for national climate policies. The figure shows the change in costs (or gains in case of a negative cost) from a weakening of the global ocean carbon sink by 5 and 10 % for a scenario without emissions reductions trading (A) and for a scenario with full emissions reductions trading (B). The figure includes the ten major industrialized and developing regions in international climate policy. Error bars represent ±1 SD for the national CO_2 abatement cost/gain (in percent).

Countries are indicated by their ISO3 code: CHN China, USA United States EU29 European Union 27 with Norway and Iceland, IND India, RUS Russia, JPN Japan, KOR South Korea, CAN Canada, BRA Brazilian, AUS Australia.

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Yet, the prospects of ocean-based CDR also depend on the question of which states and actors are responsible for carrying it out. Assuming that National Determined Contributions (NDCs) are increased in proportion to exclusive economic zones to compensate for a possible weakening of the global ocean carbon sink. In Figure 5 the change in costs is shown for a weakening of the global ocean carbon sink of 10 % for NDCs, with high ambition levels under the assumption of no and full emissions reductions trading (Panel a and b, respectively), displaying the ten major industrialized and developing regions in international climate policy (Rickels et al., 2024). The CO_2 price and its response due to the allocation of additional reduction requirements provide information on the incentives to include marine CDR. Assuming a weakening of the ocean carbon sink and the suggested allocation of additional emission reductions, the national CO_2 prices in three potential CDR markets, the United States, EU29, and Japan, increase from USD/tCO_2 55.81 (SD 22.61), 101.51 (SD 36.03), and 151.67. (SD 46.24) to USD/tCO2 63.25 (SD 23.43), 129.95 (37.80), and 169.48 (SD 46.41), respectively (Rickels et al., 2024). Accordingly, the economic prospects of marine CDR methods like macroalgae farming and harvesting or OAE would increase under such an allocation of the liability for the ocean carbon sink.

Still, actually realizing the CDR potential of ONETs requires robust MRV. Accounting issues cannot be addressed in isolation from the governance framework and in turn, different accounting methods to determine the climate benefit and different designs to organize the issuance of carbon credits can be appropriate. For example, the intra-country emissions trading in the EU for the sectors covered by the Effort-Sharing-Regulation, the NET method is appropriate (and actually applied) in determining the crediting of removals. Compliance systems could be aligned with carbon accounting under cost-benefit considerations by introducing an intermediary institution that buys the international offsets and resells (a fraction of) them to the domestic compliance system, at the same time assuming the liability for non-permanent storage, i.e. by buying back an equivalent amount of allowances from the market.

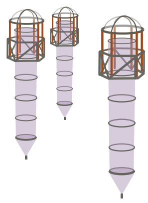
(B) Scalability and responses to ONETs

Assessments of the scalability of ONETs on global and regional scale, as well as their impacts, have often been based on idealized scenarios that take little account of technical and logistical constraints. Early modelling studies have shown hypothetical, wide-spread implementations of ocean alkalinity enhancement (OAE) appear to be an ONET option where the ocean can remove additional Gigatons of CO_2 from the atmosphere every year, if applied globally (Ilyina et al., 2013; Köhler et al., 2013). To put the ONET-induced additional oceanic CO_2 uptake rates into perspective, the global CDR potential of terrestrial sustainable BioEnergy with Carbon Capture and Storage (BECCS) has been estimated to range between 2 and 4 $GtCO_2\ yr^{-1}$ by 2050 while accounting for environmental constraints (NEGEM, 2024). In the NEGEM project, some model evaluations using TIMES, a tool for exploring future energy pathways and their costs, considered ocean liming (OL) as one contribution to an emission reduction portfolio, reaching about 2 $GtCO_2\ yr^{-1}$ of abatement between 2080 and 2090 (see also **van Kooten et al., 2023**, **D1.4**). Of all the different ONETs, such as artificial upwelling or ocean iron fertilization, the scalability of OAE is the most effective (Keller et al., 2014), with a marine CDR potential of 7 – 8 $GtCO_2\ yr^{-1}$ assuming restricted but still highly optimistic deployments of alkalinity via OL. OceanNETs has specifically addressed the need for more realistic scenarios to achieve more plausible results.

Electrochemical brine splitting (EBS) and OL are specific types of OAE that show particular promise as due to their suitability for upscaling and relatively minor environmental impacts (**Campbell et al., 2024**, **D6.6**). In the case of OL, there is potential for using available capacity in the cement and lime industries. EBS can potentially exploit waste desalination brines. More detailed analysis focused on deployment of OL, EBS, and coastal enhanced weathering in Spain. On global scale, the deployment scenarios accounted for regional differences in the availability of resources and infrastructure. In OceanNETS, the results of these in-depth analyses are considered as more realistic scenarios for OAE, which were used as constraints for Earth- system- and regional ocean model simulations. In parallel to the development and evaluation of the high-fidelity OAE scenarios, experimental studies have provided important novel insights, used in determining potential abiotic and biotic effects of OAE on marine chemistry and the plankton ecosystem respectively.

Mesocosm experiments serve as a crucial intermediary between the highly controlled yet limited realism of laboratory studies and the inherent complexity of natural marine ecosystems. This approach is especially valuable for assessing potential OAE strategies, as it enables a comprehensive understanding of critical processes, such as dissolution and precipitation kinetics and responses in the plankton ecosystem dynamics (**Riebesell et al., 2023**). The intensity of the OAE impact on plankton growth is primarily determined by the availability of CO_2 and hydrogen carbonate (HCO_3^-) needed for algal growth. Non-equilibrated seawater of enhanced alkalinity has a greatly reduced CO_2 concentration and it can take a year and longer before an equilibration of atmospheric and oceanic CO_2 between is achieved. Experimental safe-case studies that account for an equilibration between atmospheric and oceanic CO_2 partial pressure cause OAE conditions under which the availability of carbon for primary production should not become limited, because carbon is already added to the water volume prior to its deployment, thereby keeping pH at natural levels as well. The latter approach requires pre-processing of the seawater before deployment. When used as a marine CDR option, the CO_2 introduced into the seawater with increased alkalinity should either have been extracted from the atmosphere directly or may have been captured from industrial emissions (e.g., by extensive and effective bubbling). The latter case could be critical with regard to other gases that could enter the treated seawater unintentionally. In principle, the approach of deploying CO_2-equilibrated seawater of enhanced alkalinity would facilitate the MRV of carbon sequestration, bypassing the otherwise required time period for natural air-sea gas exchange and the uncertainties involved. It would also limit negative impacts on the environment. Ultimately, both CO_2-equilibrated and non-equilibrated conditions were investigated in the mesocosm experiments.

Experimental observational studies



The two mesocosm OAE studies conducted within OceanNETs (Gran Canaria, Spain, 2021 and Bergen, Norway, 2022) represent a significant advancement in our understanding of the environmental and ecological risks, as well as the co-benefits, associated with OAE applications. These studies yield first comprehensive data sets on the impacts of OAE on biodiversity, ecosystem functioning, and the biogeochemical cycling of natural plankton communities and the provided data will serve as a foundational resource for a thorough assessment of the safe operational boundaries for OAE applications. The conducted geochemical side experiments provided a sophisticated knowledge base about upper geochemical threshold values for OAE application scenarios to prevent carbonate precipitation due to oversaturation.

The first experiment was conducted with subtropic, oligotrophic (nutrient-depleted) seawater of Gran Canaria, Spain (**Riebesell et al., 2022**, **D5.4**; **Riebesell et al., 2024**, **D5.6**). It was designed to describe a potentially safe operation of OAE under CO_2-equilibrated conditions, assuming an idealised scenario in which seawater of enhanced alkalinity has already absorbed atmospheric CO_2 before being released into the ocean (**Hartmann et al., 2023**; **Paul et al., 2025**; **Marín-Samper et al., 2024a**). Provided that the alkalinity is increased along with additional dissolved inorganic carbon (DIC) so that the natural pCO_2 in the seawater is unchanged, the resulting shifts in pH and carbonate chemistry remain marginal. In the Gran Canaria 2021 experiment, the mesocosms differed in terms of their intensity of alkalinity addition. The different intensities were arranged in nine steps, covering a range from zero to a doubling of the natural alkalinity on site. The covered range of CO_2 -equilibrated OAE induced elevations in pH and aragonite saturation state (Ωa) of no more than 0.22 and 6.7, respectively.

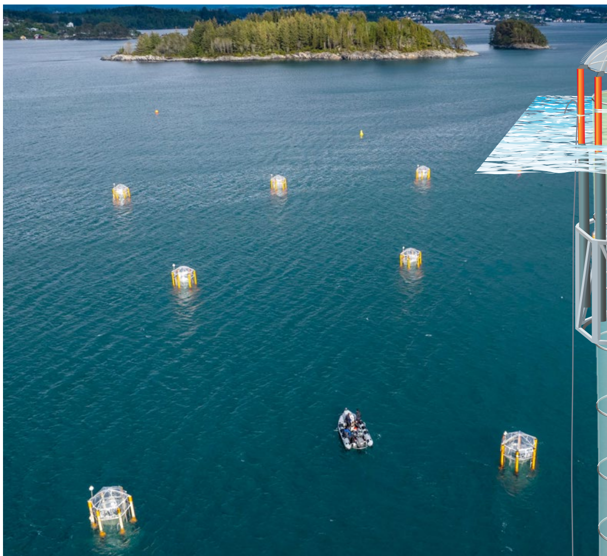
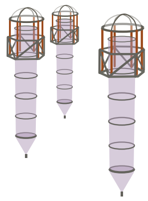


Figure 6: Two mesocosm experiments: on-shore mesocosms (left), employed on Gran Canaria, Spain, and the Off-Shore Mesocosms for Ocean Simulations (KOSMOS), here employed in the Raunefjord nearby Bergen, Norway.

In a second experiment, the Bergen 2022 campaign, with Off-Shore Mesocosms for Ocean Simulations (KOSMOS; Riebesell et al., 2023), some more critical, mineral-based OAE scenarios were considered in a non-equilibrated approach. Under these conditions, substantial shifts in seawater carbonate chemistry occur and the air-sea gas exchange of CO_2 is too slow to achieve an equilibration between seawater and atmospheric CO_2. The upper limit of alkalinity enhancement in this experiment was 600 µmol kg^{-1}, which was 27 % higher than the natural alkalinity level at that site (Marín-Samper et al., 2024b; Suessle et al., 2025). With this alkalinity range covered, the observed increase in pH remained smaller than 0.7 and Ωa did not exceed 5.5.

The experimental design included two mirrored gradients of enhanced alkalinity, to distinguish between silicate- and carbonate-based effects. Mineral sources such as olivine can release elements like silicate and nickel that interact with marine biology (Xin et al., 2024a). Instead of olivine, the silicate-OAE involved adding sodium metasilicate (Na_2SiO_3) across the gradient, with magnesium dosed in proportion to alkalinity. Carbonate-OAE followed the same proportionality, substituting calcium instead.

KEY FINDINGS



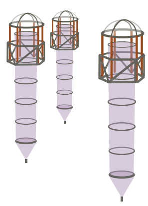
MESOKOSM STUDIES
OCEAN ALKALINITY ENHANCEMENT

i) Impacts of OAE on plankton ecology: During the Gran Canaria campaign, it was found that CO_2-equilibrated OAE had few impacts on the oligotrophic plankton community, with only minor biogeochemical and ecological responses observed across the alkalinity gradient (see Table 4). Notably, abiotic mineral precipitation occurred in the three highest alkalinity treatments. These observations provide critical insights into the upper alkalinity limits, beyond which the risk of alkalinity leakage rises and CDR efficiency decreases (Suessle et al., 2025). Most biogeochemical pools remained stable, with the exception of some effects linked to organic nitrogen dynamics – suggesting that nitrogen turnover processes may be particularly sensitive to OAE (Paul et al., 2025). In terms of plankton dynamics, the only notable phytoplankton response was the bloom of Chrysochromulina parkaea, a non-calcifying, nano-sized haptophyte (Xin et al., 2024b). These blooms appeared in a subset of alkalinized treatments, despite low inorganic nutrients, but no clear linear relationship with OAE treatment intensity was detected (Paul et al., 2025). The zooplankton community also appeared largely resilient to OAE, with no observed impacts on its role as a food source for fish – indicating the potential robustness of the ecosystem service of food production (Sánchez et al., 2024). Finally, carbon export indicators showed no response to OAE, suggesting that this ecosystem function, too, may be resilient under the tested conditions (Suessle et al., 2025).

During the Bergen 2022 campaign, more pronounced effects of OAE emerged, though the plankton community and associated ecosystem functions largely remained resilient (Table 4). One key focus was the CO_2 re-equilibration times relevant for MRV in carbon sequestration, as this experiment tested an unequilibrated OAE approach. Under the highest alkalinity addition (ΔTA) tested, it is estimated that CO_2 re-equilibration would take over three years (Schneider et al., 2025), implying that low CO_2 conditions – potentially detrimental to photosynthetic organisms – could persist for extended periods. However, community metabolic rates indicated that phytoplankton were resilient to carbonate chemistry changes even under low pCO_2 conditions (Marín-Samper et al., 2024b). Specifically, calcifiers (coccolithophores) remained more abundant than the silicifiers (diatoms) throughout the experiment, even following nutrient addition midway through (Kittu et al., in prep.). Both calcification rates and coccolithophore abundances followed an optimum response to increasing alkalinity, peaking between ΔTA 150 and 300 µmol kg^{-1}, particularly after nutrients were added (Schneider et al., 2025; Kittu et al., in prep.).

Table 4: Summary of responses to Ocean Alkalinity Enhancement (OAE) across plankton foodweb during the mesocosm experiments in Gran Canaria, Spain (CO_2-equilibrated) and Bergen, Norway (non-equilibrated). Responses according to linear regression analyses are indicated by symbols: '=' no significant effect, '↑TA' and '↓TA', increase or decrease with alkalinity respectively. Exceptional (non-linear) responses are represented by 'x{2}' (polynomial second order fit for net community production), and '∩' (optimum curve, coccolithophore abundance). In Gran Canaria, the campaign was divided into a shorter- (days 5 – 21) and a longer-term phase (days 22 – 34). In Bergen, the plankton was exposed to OAE based either on silicate (Si) or on carbonate (Ca) minerals, comprising a nutrient-depleted phase and a nutrient-replete phase (after day 26). Here, the symbols are complemented by the mineral (in brackets) where an effect was observed; '↑Si' = increase in silicate regardless of alkalinity; and 'int. ( )' = significant interaction between mineral type and alkalinity, with the mineral driving the response in bracket.

	Responses to Ocean Alkalinity Enahncement (OAE)			
	Gran Canaria 2021		Bergen 2022	
	CO_2-equilibrated		Non-equilibrated	
Ecosystem state	**shorter-term phase**	**longer-term phase**	**nutrient-deplete phase**	**nutrient-replete phase**
Composition				
Particulate organic carbon (POC)	=	=	=	=
Particulate organic nitrogen (PON)	↓TA	=	↓TA (Si)	=
POC:PON ratio	=	↑TA	=	int. (Si:↑TA)
Chlorophyll-*a* (*phytoplankton*)	=	=	=	=
Abundance of calcifiers (*coccolithophores*)	=	=	int. (↑Si)	∩TA
Abundance of silicifiers (*diatoms*)	=	=	=	int. (↑Si:↑TA)
Zooplankton biomass	=	=	=	=
Zooplankton C:N ratio	↑TA	=	=	↓TA
Zooplankton copepod:gelatinous ratio	=	=	=	=
Zooplankton fatty acids	=	=	n.a.	n.a.
Fish C:N ratio	n.a.	n.a.	n.a.	=
Productivity				
Net community production	=	x{2} TA	=	=
Production of (large) zooplankton	↓TA	=	=	=
Reproduction of *copepod nauplii*	↓TA	=	=	=
Fish (biomass) production	n.a.	n.a.	n.a.	↑TA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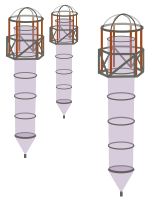
The impact of OAE on silicification rates was mainly species-specific (Ferderer et al., 2024), but the overall contribution of diatoms to the total chlorophyll-a was not significantly different between minerals (**Kittu et al., in prep.**). Across all diatom groups investigated, silicification in *Pseudo-nitzschia* spp. increased significantly with rising alkalinity across both mineral treatments, while *Nitzschia* spp. showed enhanced silicification only in the silicate-based OAE treatment. The OceanNETs results indicate that while OAE may have limited effects on diatoms, its impact on silicification could vary between genera or species (Ferderer et al., 2024).



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In contrast, the zooplankton community showed resilience, despite observed effects on both bottom-up and top-down controls (Sánchez et al., in prep.). During the nutrient-limited phase, low food availability may have buffered indirect OAE effects (such as the ones reported for coccolithophores and diatoms), while in the nutrient-rich phase, fish predation likely reduced zooplankton biomass, potentially masking OAE effects. Copepods and larvaceans were closely examined, but no treatment effects were found on respiration or reproduction in copepods, nor on feeding in larvaceans – suggesting physiological resilience to the OAE scenarios tested (Couret et al., in prep.; Bhaumik et al., in prep.). Lastly, fish appeared not only tolerant to the chemical shifts induced by OAE but potentially benefited from them, as indicated by an increase in biomass with rising alkalinity (Goldenberg et al., 2024).

ii) Secondary precipitation of calcium carbonates: To avoid excessive supersaturation of calcium carbonates, which can lead to precipitation, the use of an alkaline solution that is already in CO_2 equilibrium with the atmosphere is more advantageous than the use of slurried solid particles which can act as nuclei for precipitation (Hartmann et al., 2023). The formation of secondary minerals due to oversaturation during OAE applications sets upper limits on their efficiency and thus CDR potential. As two of the first experimental studies analyzing the effects of OAE on precipitation, Hartmann et al. (2023) and Suitner et al. (2024) could describe the effects and consequences of such precipitation events. Within alkalized systems without sufficient potential for dilution with untreated water, the process of runaway carbonate precipitation could even lead to a net-loss of alkalinity (Moras et al., 2022) and should therefore be avoided in natural systems. During side experiments on Gran Canaria 2021 (Hartmann et al., 2023; Paul et al., 2025) and the Bergen 2022 campaign (Suitner et al., 2024; 2025), the temporal evolution of the runaway process could be parameterized, allowing for the articulation of upper alkalinization threshold levels (Figure 7, from Suitner et al., 2024).

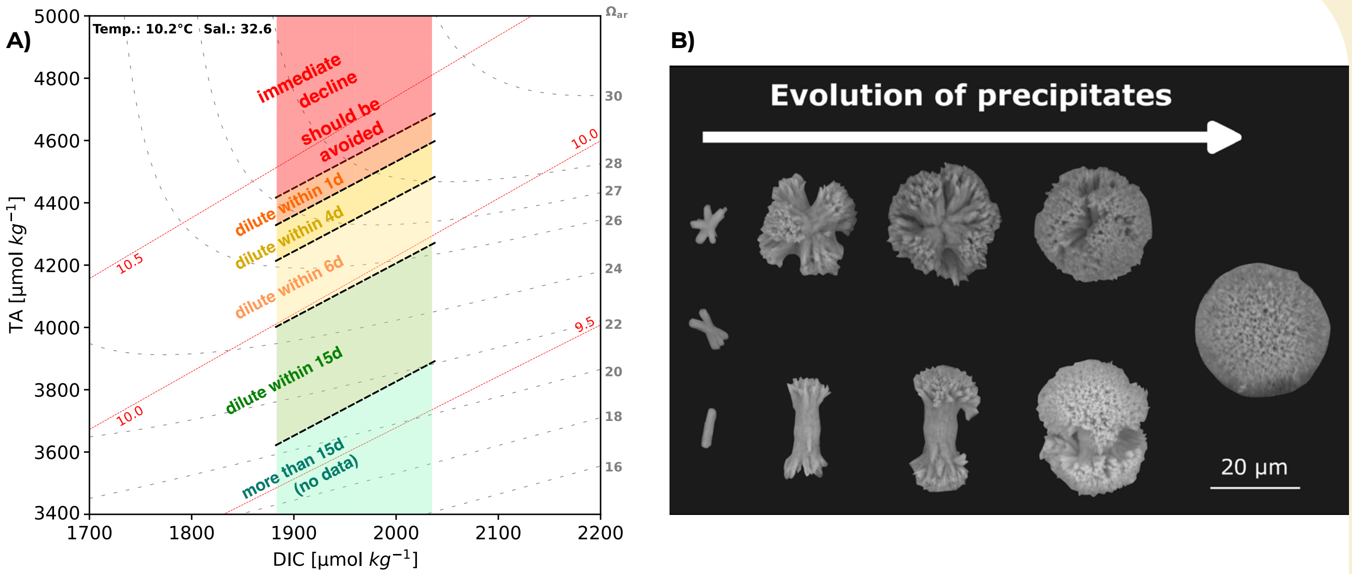
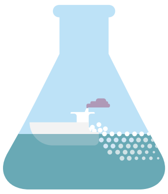


Figure 7: A) stability ranges during non-CO_2-equilibrated experiments showing upper critical limits for OAE application scenarios, B) scheme of the evolution of precipitates, showing a selection of precipitated particles in different development stages.

Case studies of OAE



CASE STUDIES
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A significant challenge in many negative emission proposals is to formulate realistic deployment scenarios for associated technologies. The case studies carried out in OceanNETs focused on two ONETs options: ocean liming (OL) and electrochemical brine splitting (EBS). The research work provided a tangible framework for others to deliberate on OAE, and developed the 'realistic' deployment scenarios that could then be integrated into Earth system models or were used for regional model applications. The environmental assessment activities were extended beyond OL and EBS, with additional life cycle assessments (LCA) focusing on electrochemical weathering and coastal enhanced weathering technologies (CEW). The LCAs of these OAE approaches provided detailed insights into the energy, water, and material demands. During OceanNETS it was explored how these technologies might be implemented in practice, helping to assess their technical feasibility, resource needs, environmental impacts, and potential risks.

A major concern of the OceanNETs research were the energy demands (e.g., CO_2 footprints) and the estimation of realistic industrial capacities of utilizing (mining) some feedstock that can be processed into material that can potentially be available for OAE. Plausible OAE deployment scenarios were derived by analyzing LCAs. Equally important, stakeholder consultation workshops provided critical insights into technical, policy, and social considerations. These consultations were essential for informing social impact assessments and guiding responsible deployment.

Figure 8, adopted from **Eisaman et al.**, (2023), illustrates the major differences between OL and EBS, as reflected in the LCAs and the type by which alkalinity becomes distributed in the seawater. The actual potential availability of the respective resources (alkalinity sources) was determined and the capacity to process these resources via the existing industrial infrastructure was assessed, taking into account in particular:

- The conversion of spare capacity within the European and Chinese cement industry using limestone minerals to create quicklime (calcium oxide, CaO) or slaked lime (calcium hydroxide, $Ca(OH)_2$) for OL.
- Pathways of EBS using waste desalination brines in the European and Middle Eastern desalination industry.

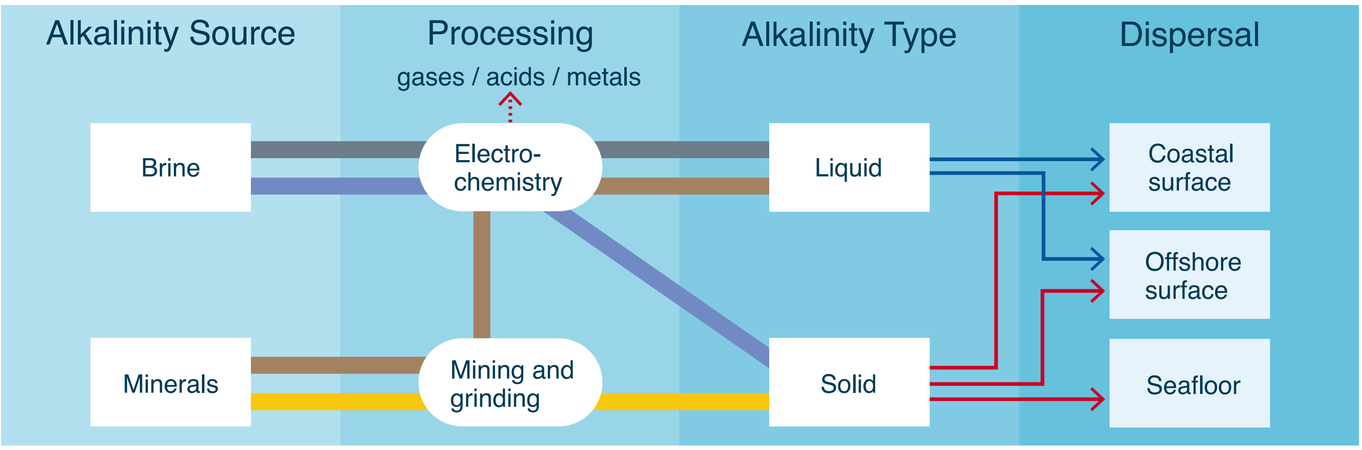
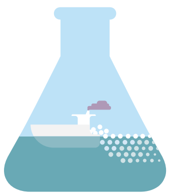


Figure 8: Different OAE approaches (EBS, upper branch; OL lower branch) categorized by alkalinity source, processing method, alkalinity type and location of dispersal (deployment region), according to Eisaman et al., (2023). Each path color represents a unique operational task.

Background descriptions of cement/lime production and the desalination industry are provided in **Lezaun et al.** (2021, **D6.1**). The corresponding LCAs are described in **Foteinis and Renforth** (2021, **D6.2**). The research involved in these two preceding studies is presented in Foteinis et al. (2022), which includes schematic descriptions for OL, which were additionally supplemented by information from stakeholders. A related workshop (December 2021) is summarised in Lezaun and Valenzuela (2021, **D6.3**). The potential deployment of OL and EBS is described in Campbell et al. (2023, **D6.4**), with a focus on Spain, where there are significant limestone resources, spare capacity in existing cement kilns, and a growing desalination industry. Also described in Campbell et al. (2023, **D6.4**) was the promise of Spain for CEW technology. In the two policy briefs of Lezaun and Valenzuela (2024a, b, **D6.5**) the results of the realistic deployment scenarios are synthesized for the benefit of government and non-governmental organisations interested in science-based OAE policy.

KEY FINDINGS



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In Campbell et al. (2024, **D6.6**) key findings of all case studies are summarized, with a focus on OL and EBS. In general, the technological efficiency and sustainability of OAE applications turn out to be suited for removing gigatons of CO_2, particularly if powered by renewable energy resources. In case of OL, the potential for CDR depends on the kiln type used for calcination and fuel type, and it is sensitive to transportation means and distance (e.g. between sites of limestone extraction and comminution, as well as transport of slaked lime to the ocean). One common problem for OL is the high thermal energy requirement of existing calciners, required for $CaCO_3$ decomposition to CaO. Since the calcination produces CO_2, the actual key challenges include the minimization of the CO_2 footprint during this particular step in the process cycle of OL (Figure 9, refined from Renforth et al., 2013). Foteinis et al. (2022) clarifies that the calcination process alone contributes significantly to the overall carbon footprint, emitting 298 kg CO_2-equivalent per ton of captured CO_2. The results demonstrate that the least efficient kiln would increase the carbon footprint by 82 % compared to the baseline scenario, while the most energy efficient kiln could reduce it by 18 %. By adopting clean, energy-efficient technologies such as solar calciners and utilizing renewable energy sources like biomass or hydroelectric power, the process cycle of OL can be optimized. Thus, the use of green energy should be a prerequisite for all examined technologies. Additionally, Carbon Capture and Storage (CCS) systems should be developed to reduce process emissions and minimize the carbon footprint of OAE. Following the idea of Renforth et al. (2013), the calcination step could occur within the cement industry's pre-existing spare kiln capacity, without the need to construct new kilns and grinding circuits. Accordingly, it has proven

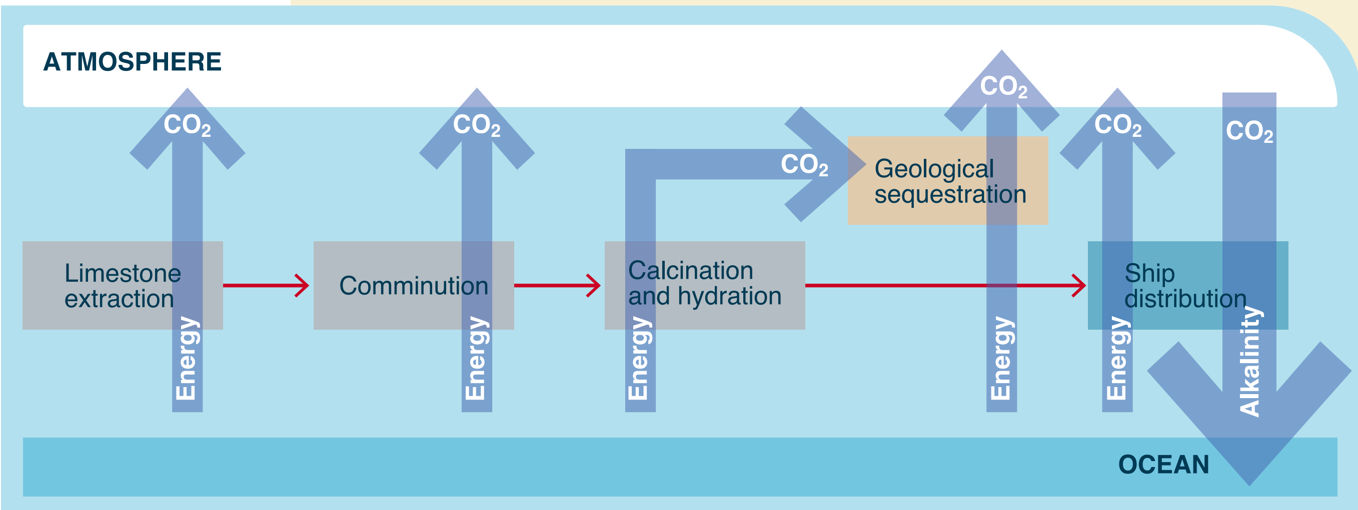

Figure 9: Schematic representation of major steps of the process cycle of OL, based on illustration of Renforth et al. (2013).

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more expedient to integrate CCS into existing industrial processing of lime (Campbell et al., 2023, **D6.4**). IEA (2018) suggests that CCS deployment may reach 88 % by 2050, increasing from ~20 % in 2030. Specifically, it has been suggested that CCS and relevant technologies will approach maturity for commercial deployment between 2020 and 2035 (after 2030 efficiency will be nearing optimisation), while in the 2035 – 2050 they could be deployed rapidly (Rissman et al., 2020).

The potential of Spain for OAE applications is highlighted due to its industrial infrastructure in the cement and desalination sectors, relevant to exploitation of OL and EBS respectively, and beach nourishment for CEW. Brines, e.g. as obtained in desalination plants, could potentially provide an abundant source of alkalinity through their electrochemical processing to produce aqueous NaOH(aq) or other hydroxides. These can be used for almost immediate OAE and can generate a CDR of 1.8 $MtCO_2$ per year in the coastal areas of Spain alone. Spain's total CDR capacity via OAE amounts to 24.4 $MtCO_2$ per year, with contributions of 22.6 $MtCO_2$ per year from OL, assuming that these processes are powered exclusively by renewable energy (Campbell et al., 2023, **D6.4**). Finally, the results underline the importance of holistic approaches that encompass environmental, economic and social dimensions as a way of achieving the climate neutrality targets by 2050.

For the derivation of the OAE scenarios, historical data were analysed, focusing on spare capacities in cement and lime plants, as well as previous expansion rates of limestone extraction (Foteinis and Renforth, 2021, **D6.2**). Based on the historical data analysis, maximum annual expansion rates for hydrated lime production are assumed to be 7 % in a high-growth scenario and 5 % in a low-growth scenario (Figure 10). Accounting for the potential use of spare industrial capacity through mid-century, total production in Europe that could be made available for OL may scale to 100 – 150 Mt per year by 2100 (middle panel of Figure 10). It is assumed that any new production capacity will be subject to climate regulations requiring zero net greenhouse gas emissions. This would be achieved through a combination of carbon capture and storage, renewable energy use, and process efficiency improvements. The ability to utilize spare capacity will also depend on the extent to which carbon capture technologies are going to be deployed. Under these conditions, emissions

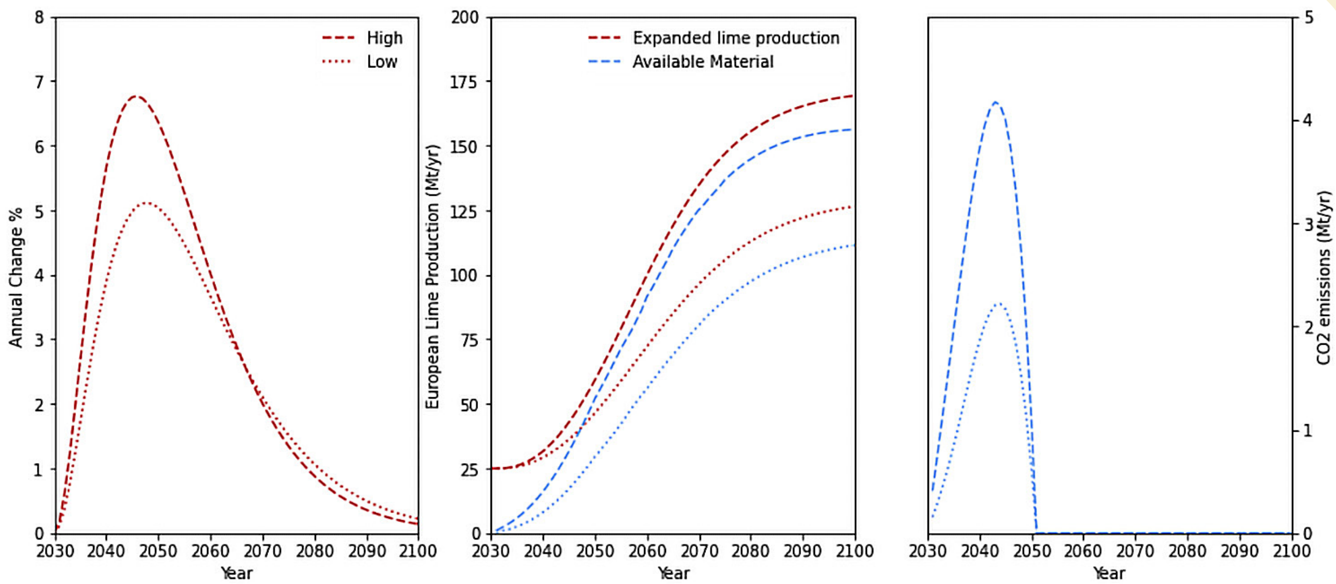
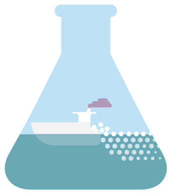


Figure 10: Annual percentage change of projected rock extraction scenarios in Europe (left) and the associated high and low production scenarios for hydrated lime (slaked lime) available for ocean liming (middle), and the corresponding CO_2 emissions from production.



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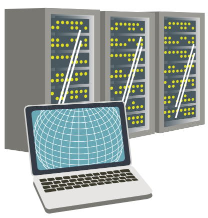
from hydrated lime production are expected to be relatively low and temporary, particularly as wider industrial and economic decarbonization efforts take effect in the second half of the century. The derived OAE scenarios describe the projected spare capacities of hydrated lime available for OL. The regional implementation of OAE (how much and where) then determined the setup of subsequent simulations with ocean models and Earth system models (Partanen and Bergman, 2024, **D4.6**).

Modelling

Earth system models (ESMs) remain the only available tool to investigate the global efficiency (including Earth system feedbacks) of CDR approaches. For OceanNETs, a large number of ESM simulations were conducted and analyzed, ranging from stylized and exploratory simulations to the implementation of realistic deployment scenarios, based on the historical analyses of spare capacities of lime production, LCAs, and other constraints derived from OceanNETs results. When possible and pertinent, ensembles of models of different complexity and resolution were used to provide estimates of uncertainty. Most simulations have been performed with freely evolving carbon-cycles ("emission-driven") and with interactive deployment of CDR, placing these simulations at the forefront of research.



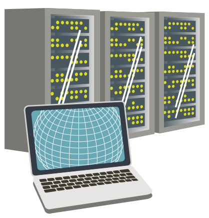
MODELLING

Using ESMs to assess marine CDR requires a sufficiently high fidelity of the models in simulating the marine carbon cycle and the processes that impact (and/or are impacted by) marine CDR. Some of these processes are not well represented or missing in models, and it is important to establish the impact of such potential shortcomings on the simulation of marine CDR. In OceanNETs, the fidelity of 14 CMIP6 ESMs was evaluated as to their ability to represent the present-day distribution of alkalinity and pH compared to observations, and how sensitive the models are to OAE (Hinrichs et al., 2023, **D4.4**). Sensitivities of phytoplankton growth and coccolithophore calcification to changes in the carbonate system were developed from empirical studies with a focus on ocean acidification, and tested in an ocean-only model under different atmospheric CO_2 concentrations (Seifert et al., 2022, **D4.5**). In Seifert et al. (2025), these parameterizations were then tested in OAE simulations using AWI-ESM and a realistic deployment scenario, described in Sathyanadh et al. (submitted & **D4.9**). Similar to Seifert et al. (2025), the OAE impacts on plankton dynamics were investigated in a complementary study by Schartau et al. (2024, **D5.8**), also accounting for potential effects of pH changes on bacteria. In their approach the conditions of pulsed deployments were resolved instead of a continuous gradual addition of alkalinity within a defined regional 420 km^2 domain near the Canary Islands. This analysis comprises 32 pulsed OAE scenarios of varying frequencies and intensities of OAE, derived as fractions of the case-study deployment scenarios used in the ESM simulations for Europe. The effects of carbonate precipitation were explicitly resolved, and differences between local and remote CDR efficiencies were considered from an MRV perspective.

The efficiency of CDR is not only determined by how much CO_2 is removed from the atmosphere (the direct removal), but also by carbon cycle feedbacks – a weakening of terrestrial and marine carbon sinks in response to lowering atmospheric CO_2 – and finally by the reversibility of the climate system (will a previous climate state be restored by removing CO_2 from the atmosphere?). The issues of reversibility of climate change under CDR has been investigated using idealized ESM simulations (not assuming a specific CDR method; Schwinger et al., 2022). Another set of idealized OAE simulations was conducted to investigate carbon cycle feedbacks, different efficiency measures and their emission path dependency (Schwinger et al., 2024 & **D4.2**). More conceptual and less studied ideas such as macroalgae farming and sinking have been tested in a fully coupled ESM to derive first estimates of the theoretical CDR potential (Wu et al., 2023). CDR deployment has been simulated at different spatial resolutions with the same model to quantify the dependence of simulated efficiency on resolution (Keller et al., 2023, **D4.3**).

Finally, a multi-model case study of OAE deployment, based on results from Foteinis et al. (2022), was conducted with four ESMs. These were complemented by simulations of direct carbon removal (DCR), in which a comparable amount of carbon was removed instead of adding alkalinity (Sathyanadh et al., submitted; **D4.6**, **D4.9**). In addition, the concurrent deployment of OAE and BECCS was investigated (Sathyanadh et al., submitted; **D4.7**, **D4.8**). The CMIP6 emission-driven SSP5-3.4 overshoot scenario served as a background scenario for the OAE, CDR, and BECCS simulations to account for the fact that the CDR studied here would be most likely deployed as part of a CDR portfolio.

KEY FINDINGS



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i) Fidelity of CMIP6 models: Hinrichs et al. (2023, **D4.4**) showed that surface alkalinity is underestimated and deep ocean alkalinity is overestimated in most CMIP6 models, with biases stemming from both the parameterization of calcium carbonate formation and dissolution as well as model physics. Consequently, most CMIP6 models overestimate the OAE drawdown efficiency and pH increase. However, the effect on the simulated OAE efficiency remains relatively small (< 1 % deviation in efficiency), but nevertheless model improvements of the alkalinity cycle are recommended to remove disagreement.

ii) Phytoplankton responses to OAE and DCR: Seifert et al. (2022, **D4.5**) revealed that changes in phytoplankton biomass in response to OAE (or to ocean acidification) could not only be caused by direct responses to changes in the carbonate system, but also indirectly by responses to light and nutrient availability and grazing. Likewise, Seifert et al. (2025) highlight the possibility that OAE indirectly decreases net primary production (NPP) in the OAE deployment region (Figure 11B), even though the direct effect of OAE on NPP

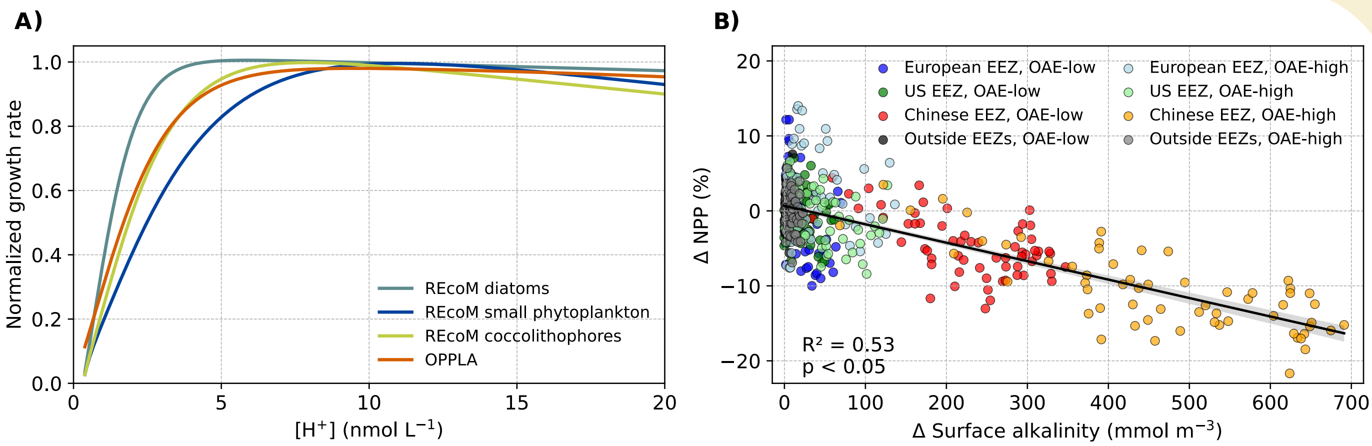
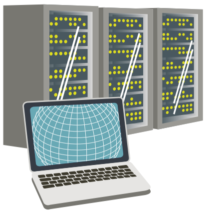


Figure 11: Modifications of phytoplankton growth by OAE. A) Parameterizations for phytoplankton growth modifications by changes in the carbonate system, as developed in Seifert et al. (2022). These parameterizations were used in the ocean biogeochemistry model REcoM for three different phytoplankton functional types. A) Responses of the normalized growth rates exemplified for proton concentrations for the respective parameterizations; the red line represents the response function used for the optimality-based plankton ecosystem (OPPLA) model in Schartau et al. (2024, D5.8). B) Correlation between OAE-induced changes in net primary production (NPP) and increase in surface alkalinity. Each dot represents one year of addition (2040-2100) in each of the deployment regions (European, US, and Chinese EEZ) as well as outside the deployment regions, for different amounts of alkalinity added (OAE-low, OAE-high). Figure from Seifert et al. (2025).



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remains small in their simulations. Furthermore, OAE-induced changes in NPP modified the efficiency of OAE in removing CO_2 from the atmosphere. Results from the OAE case-study simulations indicate that limiting the amount of added alkalinity decreased the negative effect of OAE on phytoplankton while keeping relatively high levels of carbon sequestration. On regional scale, and in case of a single annual deployment event, the plankton growth responses in Schartau et al. (2024, **D5.8**) cause relative reductions in carbon biomass of 15 % in the phytoplankton, no more than 5 % in the bacteria, and less than 1.5 % in zooplankton biomass. These periods of short-term reductions in biomass are followed by different phases of recovery. The responses in these simulations are more pronounced in the low emission SSP1-2.6 scenario than in the SSP3-7.0 model runs, clearly indicating a dependency on the emission scenario considered.

iii) Scenario dependency of OAE efficiency: It has been well known that the efficiency of OAE depends on the state of the surface ocean carbonate system and thus varies spatially and seasonally (e.g. Zhou et al., 2025). In order to investigate the dependence on future emission scenarios, a suite of idealized model experiments was undertaken (**Schwinger et al., 2024**). Results show that the efficiency of OAE is generally larger under high emissions, when the concentration of dissolved inorganic carbon (DIC) is high in the surface ocean. The reason for this effect is twofold. First the addition of alkalinity sequesters more CO_2 under high DIC conditions (**Figure 12A, B**; yellow and purple lines). Second, a higher alkalinity leads to a chemically better buffered surface ocean, which therefore takes up more CO_2 per unit of atmospheric partial pressure increase, as can be seen by the difference between the theoretical efficiency ηT and the capture efficiency ηc (compare the yellow/purple and blue/red lines in **Figure 12B**). Importantly both effects are reversed in scenarios with overshoots, where the efficiency of OAE declines after reaching peak atmospheric CO_2 concentrations (**Figure 12C**).

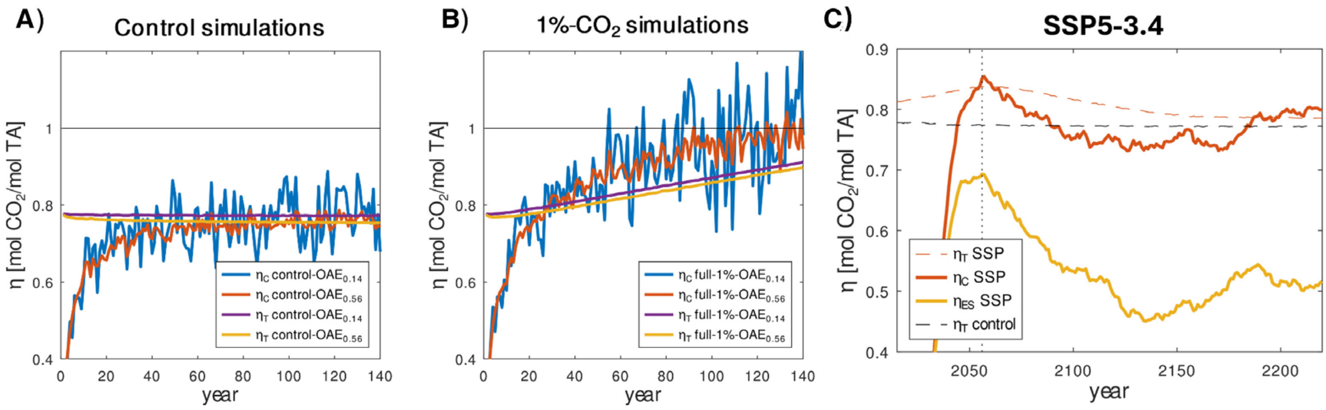


Figure 12: Efficiency of OAE (η, defined as mol CO_2 taken up per mol of alkalinity added) under (A) pre-industrial conditions, (B) in idealized experiments where CO_2 increases by 1 % per year, and (C) in the emission-driven SSP5-3.4 scenario simulation. In panels a and b experiments with two rates of OAE deployment are shown, 0.14 Pmol alkalinity per year (blue and purple lines) and 0.56 Pmol Alkalinity per year (red and yellow lines). Yellow and purple lines indicate the theoretical efficiency (η_T), assuming instantaneous equilibration of a water parcel after alkalinity addition, while the blue and red lines are the results of simulations with an Earth system model (NorESM2-LM). In panel C, the yellow line indicates the "Earth system efficiency" (η_{ES}), that is, the efficiency realized after accounting for carbon cycle feedbacks, while the red lines represent the "capture efficiency" (ηc), which excludes the contributions of feedbacks and is comparable to the efficiencies shown in panels A and B.

A clear emission scenario dependency, even without an overshoot scenario, is realized in the simulations of Schartau et al. (2024, **D5.8**), which compare efficiencies within the region of local alkalinity addition near the Canary Islands and in the surrounding area (Figure 13). These differences in OAE efficiency are also reflected on local scale for the various frequencies of pulsed OAE. In general, these simulations show how important it is to understand OAE efficiency in more realistic scenario simulations (see also Figure 14, for example).

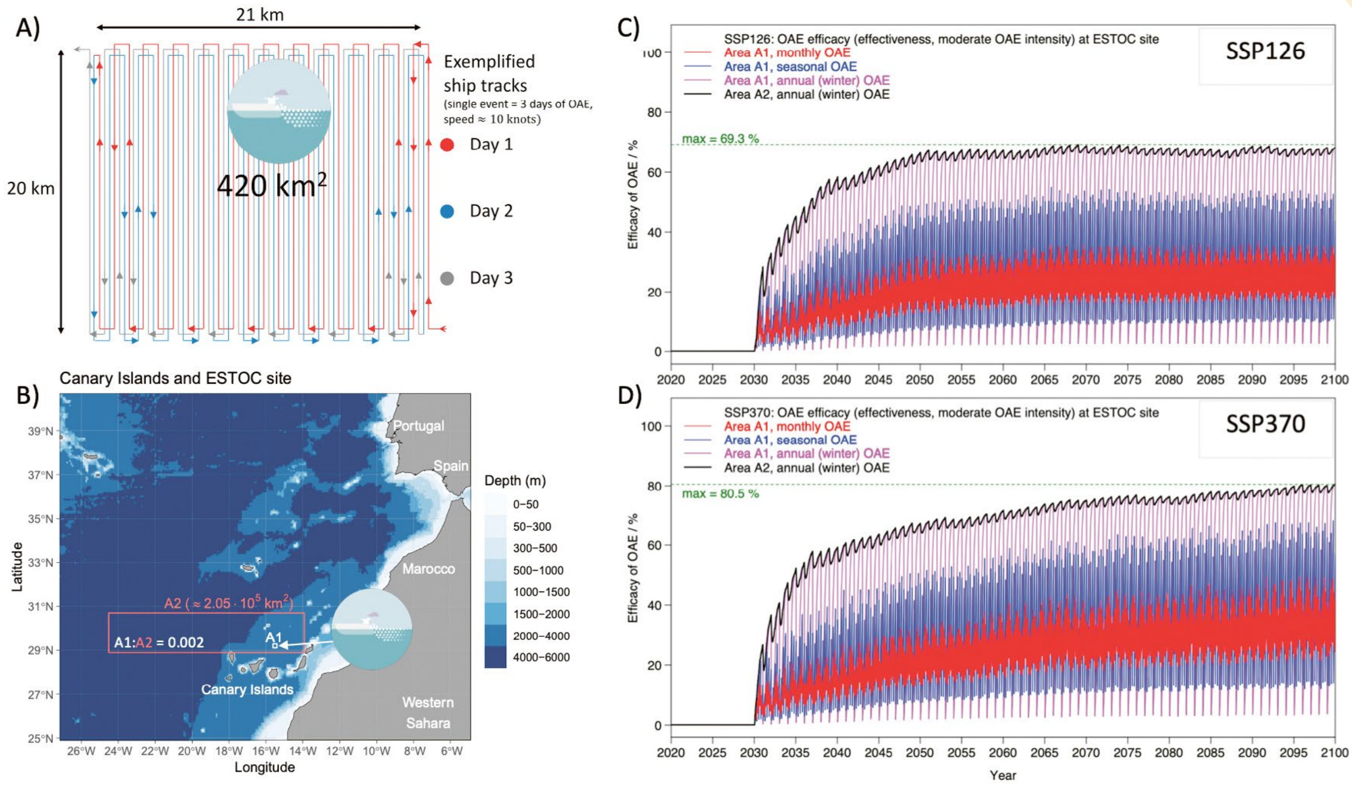
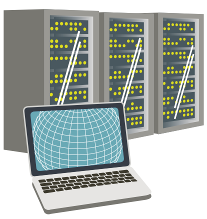


Figure 13: Regional simulations of ship-based OAE (A) within a 420 km² area nearby the Canary Islands (B). OAE efficiencies within the area of deployment and in the surrounding ocean region (C and D), with red, blue and magenta colors representing OAE of different frequencies (monthly, seasonal and annual additions). The black line indicates the efficiency away from the deployment site.



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iv) Resolution dependency of OAE efficiency: ESMs, which include a representation of the carbon cycle, often still use a relatively coarse resolution of about 1°. This is a tradeoff to facilitate the long spin-up simulations that are necessary to achieve a balanced distribution of carbon in all Earth system reservoirs. Nested model domains, where only parts of the global domain are represented in higher resolution can help to overcome these limitations. The FOCI model with a high resolution (1/10°) nest over the North Atlantic (Figure 14A) has been employed in OceanNETs to investigate the effect of resolution on marine CDR (Keller et al., 2023, **D4.3**). A comparison of OAE efficiency with and without using the high-resolution nest is shown in Figure 14 B for a high and a low emission scenario. The fact that the OAE efficiency increases in the SSP3-7.0 scenario while it decreases in SSP1-2.6 towards the end of the century is consistent with the results on the scenario-dependency described above. The effect of model resolution appears to be somewhat ambiguous. In the first part of the simulation until 2070, there is no clear effect of resolution visible. However, towards the end of the simulations, from 2070 onwards, the higher resolution model consistently shows a lower efficiency in both scenario simulations. This behaviour might be caused by

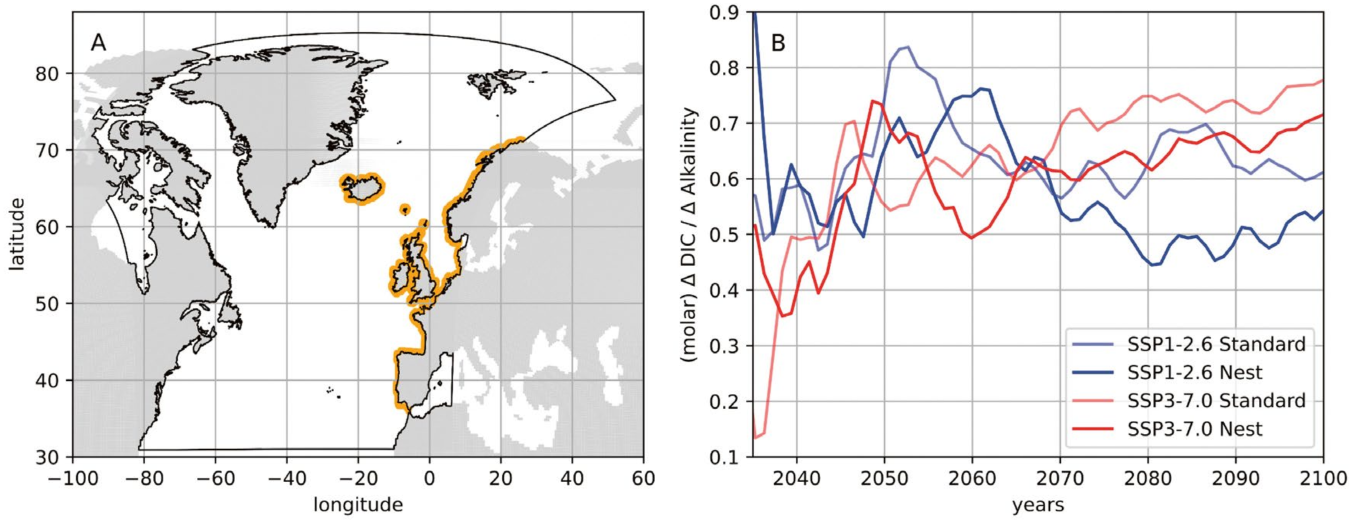


Figure 14: *A) Outline of nested model domain (1/10° resolution) in black with regions of OAE deployment along the European coasts in orange. B) Development of efficiency of OAE in the larger region shown in (A) for two climate scenarios (SSP1-2.6 and SSP3-7.0) and two model configurations (standard 0.5° resolution and nested high 1/10° resolution area in the North Atlantic). Figure from* ***D4.3*** *has been revised by Vanessa Teske.*

a stronger re-emergence of "unused" alkalinity (i.e. water parcels that did not stay long enough at the surface to equilibrate with atmospheric CO_2) in the lower resolution model. Similar paired experiments should be conducted with other ESMs that are capable of high-resolution configurations to confirm these results.

v) Case-study simulations of OAE and DCR: Results from the case-study simulations (**Figure 15**) indicate that models agree relatively well on the CO_2 drawdown from the atmosphere for a given deployment rate. In the OAE case study, assuming an optimistic but still realistic magnitude of OAE deployment of about 84 Gt CaO in coastal waters over 2040 – 2100, an atmospheric CO_2 reduction of about 8 [7-9] ppm is achieved in the four models (**Figure 15A**). This number includes the effect of carbon cycle feedbacks, i.e. a reduction of CDR efficiency due to a release of CO_2 from the ocean and terrestrial

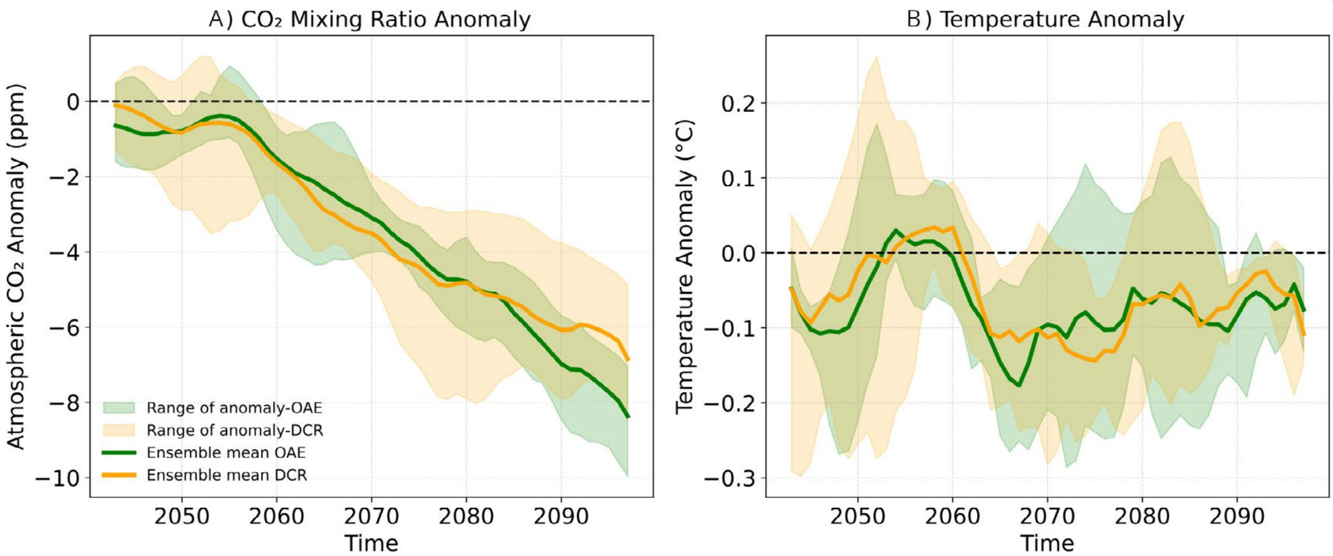
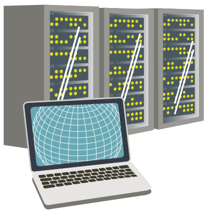


Figure 15: *Multi model mean (A) atmospheric CO_2 drawdown and (B) temperature change in the case-study simulations of coastal OAE deployment (green lines) and equivalent DCR deployment (orange lines). The shadings indicate the range of model results for the four participating ESMs (NorESM2-LM, AWI-ESM, FOCI, and EC-Earth).*



MODELLING

biosphere in response to lowered atmospheric CO_2. Although such a signal would be clearly observable in terms of CO_2 concentrations, the temperature reduction signal (Figure 15B) cannot be distinguished robustly from the variability of the climate system in the models individually. Only the multi-model mean shows a lower long-term temperature than the baseline simulations, although the reduction is still smaller than the internal variability of the system. This indicates that a temperature effect of these large-scale CDR interventions could hardly be detected in a real-world application, which raises questions about social acceptability of such costly CDR measures.

vi) Concurrent deployment of OAE and BECCS: Based on the case-study simulations with OAE deployment, additional simulations with BECCS and combined OAE+BECCS deployment were conducted with NorESM2-LM to investigate the additionality of the two methods in a portfolio of CDR (Sathyanadh et al. 2025, submitted; **D4.7/D4.8**). Results of these simulations show that the atmospheric CO_2 reduction achieved with OAE and BECCS adds linearly such that the efficiency of the combined portfolio is not reduced by concurrent deployment. However, an additive behaviour is not necessarily given for all components of the Earth system. While air-sea CO_2 fluxes combine linearly in the BECCS-OAE simulation (Figure 16A), the soil carbon content deviates significantly from this linearity (Figure 16B). As for the multi-model OAE case-study, despite significant carbon removal, temperature reductions were modest, underscoring the challenges related to larger-scale deployments.

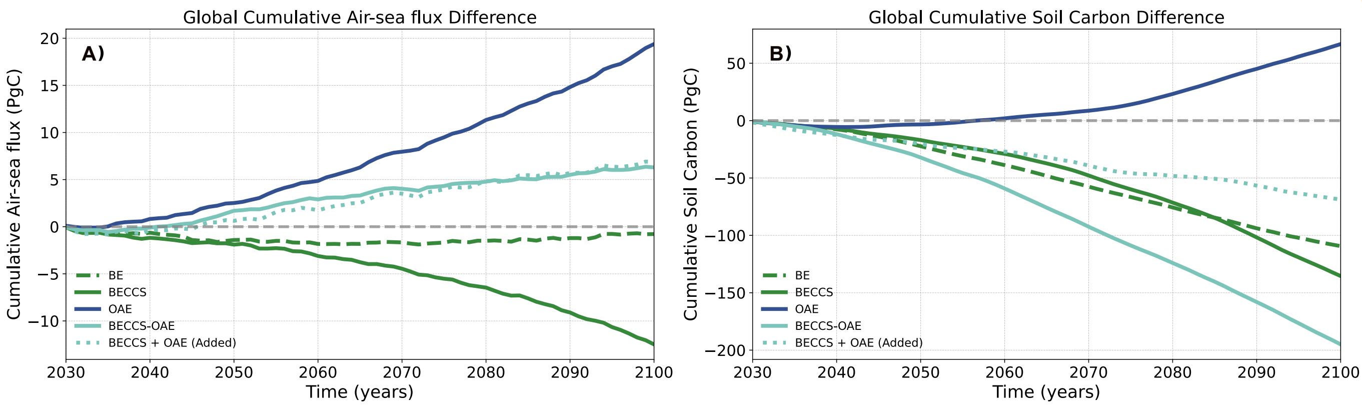
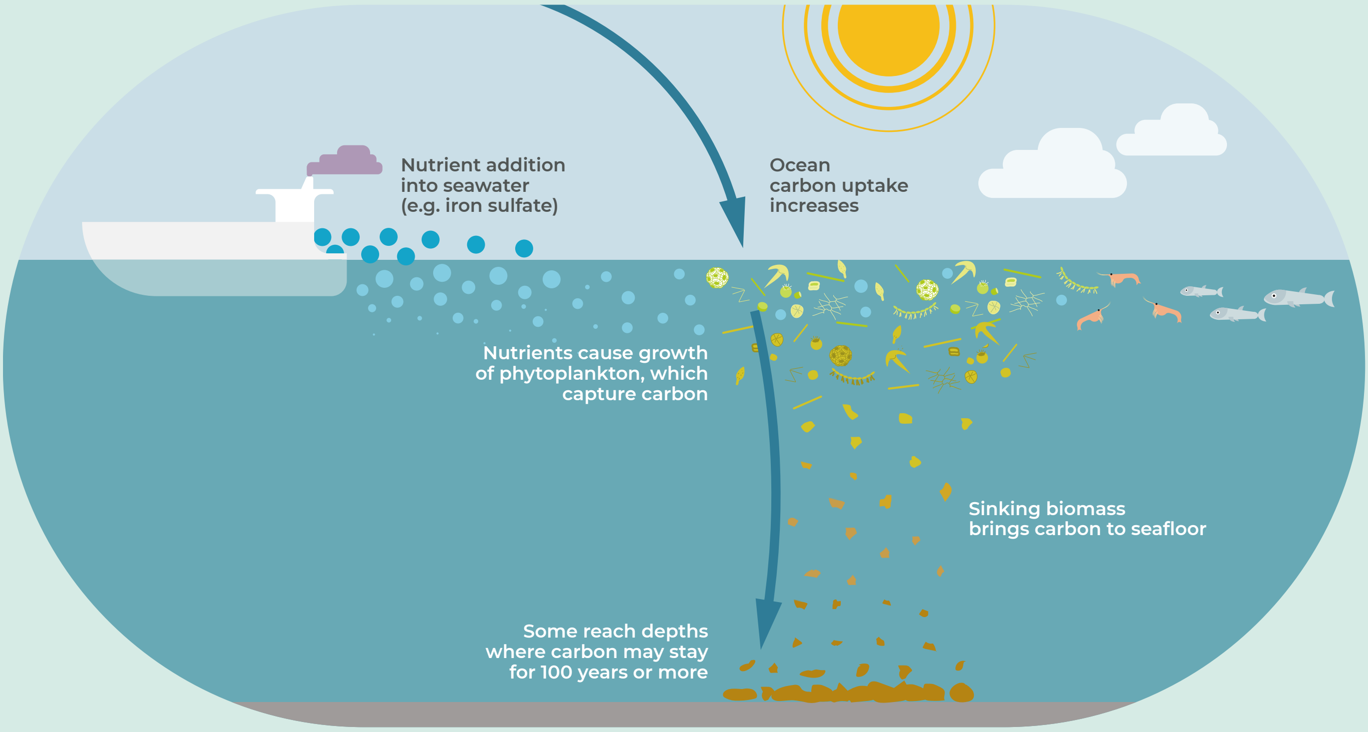


Figure 16: Global cumulative air-sea carbon flux (A) and changes in the soil carbon inventory (B) relative to the baseline with no additional CDR (the standard SSP5-3.4 scenario). Dark blue lines indicate the simulation with OAE deployment, green lines the simulation with BECCS, and the light blue lines the simulation with OAE and BECCS combined. The dashed green lines show a simulation where land-use changes are imposed as in the BECCS simulations (expansion of crop-land for bioenergy), but no CCS is done. The dotted light blue line shows the sum of the OAE-only and the BECCS-only simulation.

Ocean-based NETs research briefs

Ocean fertilization



Ocean fertilization seeks to enhance marine primary production and promote CO_2 sequestration via production and sinking of carbon biomass in the ocean (Lampitt et al., 2008). Nitrate and phosphate are macronutrients that are required in relatively high concentrations for algae growth, as opposed to micronutrients that are needed in much smaller quantities. Approximately 25 % of the upper ocean layers support only low algal biomass, even when macronutrients are abundant, because key micronutrients, particularly iron, are in limited supply, even though required only in small amounts. This scarcity is why ocean iron fertilization (OIF), rather than adding macronutrients, has attracted the most attention as a potential ocean fertilization strategy.

The addition of iron (e.g. iron sulfate) to surface ocean waters was documented to enhance phytoplankton (algal) growth (Martin et al., 1994; Coale et al., 1996). By intensifying photosynthesis, more inorganic carbon is consumed in the upper ocean layers, which in turn drives greater uptake of CO_2 from the atmosphere. The key issue concerns the long-term fate of organic carbon produced in surface waters, particularly whether it is exported to sufficiently deep ocean layers where it is remineralized and can remain for centuries or longer (e.g., Boyd et al., 2007; Yoon et al., 2018).

Public perception

Ocean fertilization projects like Lohafex or by the Haida Salmon Restoration Corporation have caused some public attention and controversies (Bertram and Merk 2020; Gannon and Hulme, 2018). Early studies found that it was perceived more negatively compared to any land-based CDR such as afforestation or direct air capture, the level of support for ocean fertilization was low (Ipsos MORI, 2010; Jobin and Siegrist, 2020) and the perceived risks were high (Amelung and Funke, 2015). Unlike afforestation it was not perceived as a 'natural' solution but as an engineering solution, falling into the same category as stratospheric aerosol injection and nuclear energy (Bostrom et al., 2012).

OceanNETs focus group participants were also skeptical. They found it difficult to form an opinion about ocean fertilization and would have liked to have more information and certainty about side-effects. There were concerns about the feasibility of ocean fertilization at scale, the controllability of algae blooms and environmental side-effects. Participants highlighted, especially in discussions about OIF (and OAE), the need to change consumption patterns and reduce emissions to target the root cause of climate change instead of relying on these methods (Veland and Merk, 2021, **D3.3**; Andersen et al., 2022, **D3.4**).

Governance

In response to an iron-enrichment experiment near the Galapagos Islands in 2007, the Contracting Parties to the London and Convention and Protocol on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (LC/LP) included ocean fertilization within their scope (resolution LC-LP.1, 2008) and deemed that ocean fertilization "should be considered as contrary to the aims of the Convention and Protocol [...]". The definition of ocean fertilization includes "any activity undertaken by humans with the intention of stimulating primary productivity in the oceans". The resolution is non-binding. A 2013 Amendment to the London Protocol (Art. 6bis) on marine geoengineering activities mandates that "Contracting Parties shall not allow the placement of matter into the sea from vessels, aircraft, platforms or other man-made structures at sea for marine geoengineering activities listed in annex 4". Ocean fertilization is currently the only activity listed in Annex 4, although a process is underway that may result in the addition of further ONETs to the regulatory scope of the LP. If the amendment were to enter into force, ocean fertilization would be directly regulated by the LP. However, to date, only six Contracting Parties have formally accepted the Amendment, whilst a two-thirds majority is needed for the Amendment to enter into force. In 2008, the Convention on Biological Diversity adopted Decision IX/16 C on ocean fertilization, which emphasizes the precautionary principle, urging that ocean fertilization activities should be limited to small-scale scientific research until there is an adequate scientific basis to justify such activities, including assessments of associated risks, and until a global, transparent, and effective control and regulatory mechanism is in place. While the Decision is not legally binding, the CBD has many more Contracting Parties than LC/LP, and the inclusion is therefore relevant.

Scalability & cost-efficiencies

A characteristic feature of hypothetical, large-scale simulations of OIF is that the global CO_2 uptake decreases over time after the onset of fertilization (Oschlies et al., 2010a; Keller et al., 2014; Tagliabue et al., 2023). The CDR potential of OIF reduces from 7.7 $GtCO_2\ yr^{-1}$, during the first year, to 1.5 $GtCO_2\ yr^{-1}$ after 55 years of OIF in the setup of Oschlies et al. (2010a). In the OIF simulations of Keller et al. (2014), phytoplankton growth is simply released from iron limitation south of 40°, leading to a CDR potential of 9.9 $GtCO_2\ yr^{-1}$, averaged over the first ten years of fertilization, which reduces to 4.5 $GtCO_2\ yr^{-1}$ when averaged over the full 80 years period. In the modelling study of Jürchott et al. (2024), in which a spatial mask of iron limitation was used as reference, a removal rate of 2.9 $GtCO_2\ yr^{-1}$ is obtained after 25 years of OIF, mainly in the high latitudes. If averaged over a 75 period of OIF, the global additional oceanic uptake is 4.7 $GtCO_2\ yr^{-1}$. These estimates describe maxima of the CDR potential induced by OIF, which are either due to a regional cessation of iron limitation or due to simplified assumptions about the input and uptake of iron by phytoplankton. Tagliabue et al. (2020) stress that major uncertainties exist with regard to the poorly known processes of biological iron cycling, i.e the separation between iron utilization by the algae and iron removal via scavenging and adsorption onto sinking particles. The climate impact of OIF is thus largely controlled by the highly uncertain relative proportions of iron uptake by phytoplankton and scavenging controls, along with the associated spatial redistribution of macronutrients (Tagliabue et al., 2023).

OIF has received the greatest attention among ocean fertilization approaches, making it the ONET option with the most results available compared with other strategies. Its CDR potential ought to reach $GtCO_2$ per year levels, with a cost-efficiency below \$100 per tCO_2 (Buesseler et al., 2024). The cost of iron itself can vary greatly depending on its origin. The most common source involves using iron salts, such as iron sulfate or iron chloride, which can be extracted from natural sources or produced synthetically. According to NASEM (2022), total costs are estimated to be under \$50 per tCO_2 sequestered. Hartmann et al. (2013) suggest that large-scale OIF could reduce costs to as low as \$10 per tCO_2. In contrast, Bednar et al. (2023) report average costs ranging from \$66 to \$158 per tCO_2, while the IPCC (2022a) provides a much broader estimate between \$50 and \$500 per tCO_2 sequestered.

Geochemical & ecological implications

It is OIF that stands out among ocean fertilization options, not only because of the attention it has received, but also due to the far greater body of research available compared with other approaches. The application of OIF can lead to significant ecological and geochemical changes (Buesseler et al., 2024). Some ecological effects are intentional and potentially beneficial, such as shifts in biomass towards larger cells (Landry et al., 2000; Schartau et al., 2010). Other outcomes are less predictable and may have unintended or undesirable consequences. Although many experimental studies clearly demonstrated that OIF stimulates phytoplankton blooms, the short- and long-term fate of the resulting organic carbon remains debated due to the wide range of ecosystem responses observed (Yoon et al., 2018). In most cases, the durations of the experiments were too short to resolve the full range of biogeochemical responses. Ultimately, the efficiency of the net transfer of CO_2 from the upper ocean layers to great depths via the export of biomass is likely dependent on the season and region where OIF is conducted.

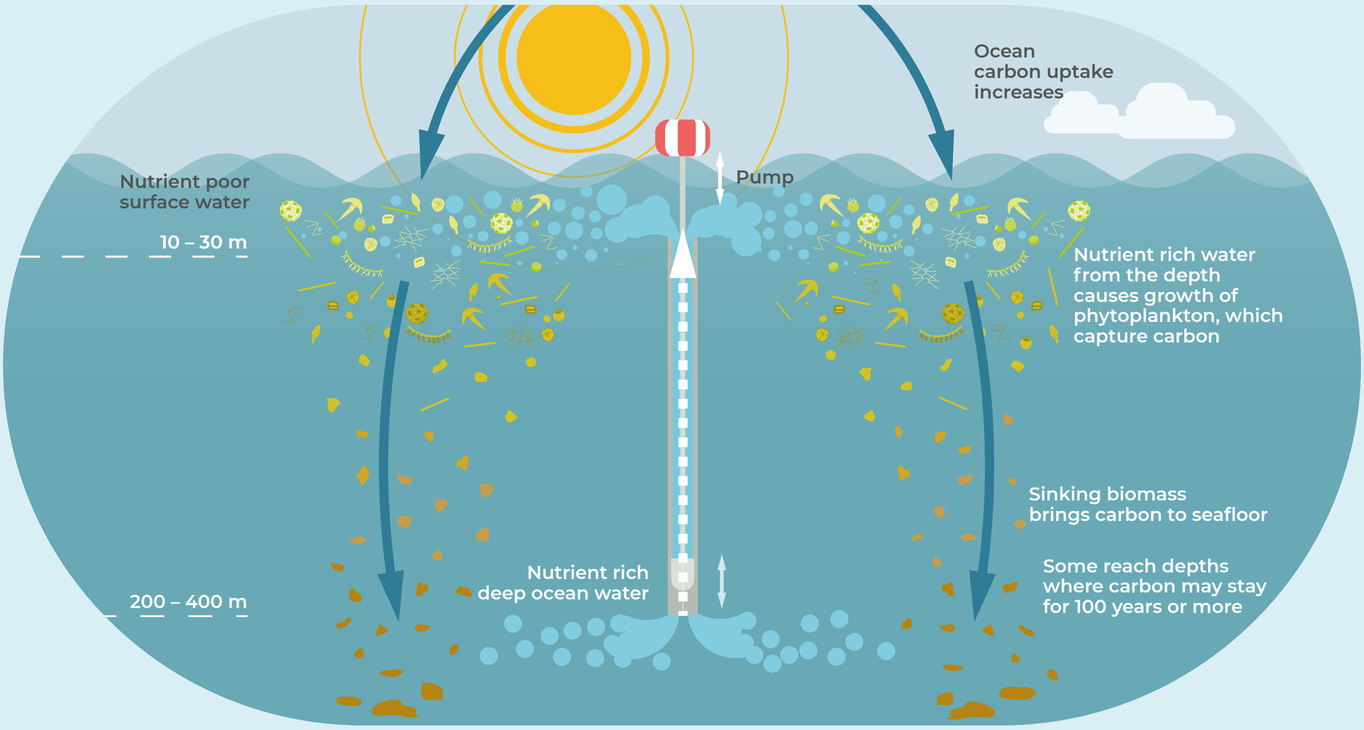
Major biogeochemical responses and potential climatic impacts of OIF, as explored through model simulations, consistently involve a redistribution of macronutrients, such as nitrate and phosphate, that leads to their gradual depletion in the upper ocean, including in regions far beyond the fertilized areas. If OIF is applied to Southern Ocean areas of iron limitation, the regionally enhanced algal growth removes those macronutrients from the upper ocean that would otherwise fuel productivity in lower-latitude regions (Oschlies et al., 2010a; Tagliabue et al., 2023). This leads to an overall decline in net primary production that offsets much of the initial carbon uptake gains.

Another considerable side-effect is the compensating back flux of CO_2 from the ocean to the atmosphere outside the OIF regions, caused by the reduction of the atmospheric CO_2. Simulation results of large-scale OIF in the Southern Ocean indicate a back flux that cancels about 19% of the additional air-sea CO_2 uptake in the fertilized region (Oschlies et al., 2010a). Important, but still uncertain, side effects comprise changes within and beyond the region of OIF, such as potential subsurface oxygen depletion, increased ocean acidification in areas where sequestered CO_2 accumulates, elevated concentrations of nitrous oxide and methane, and increased production of dimethyl sulfide (Buesseler et al., 2024).

COMPACT

Under an idealized global ocean fertilization strategy, including OIF, the aim is to promote the growth of phytoplankton biomass that captures carbon in surface waters and sinks to deeper layers. While this could lead to significant CO_2 sequestration, this ONET carries inherent risks that are shared by all variants of ocean fertilization. The sinking of organic carbon in the form of biomass, will lead to oxygen consumption at depth, potentially creating hypoxic conditions. Furthermore, the success of fertilization strategies actually depends on a carefully balanced composition of various macro- and micronutrients. Given these uncertainties and the variable carbon sequestration efficiency across oceanic conditions, the feasibility of ocean fertilization as a reliable ONET option remains limited.

Artificial upwelling



Oceanic artificial upwelling (AU) is a proposed ONET that uses long pipes to transport cold, nutrient-rich deep water to the surface. The additional nutrients stimulate primary production, thereby increasing CO_2 uptake by algae. The resulting build-up of organic carbon biomass can then sink and be exported to deeper ocean layers, where the carbon may be sequestered over long timescales. Pipe technologies under investigation include wave-driven, propeller-driven, and density-driven systems. So far, none of these have advanced beyond prototypes and model-based technical analyses (Kithil, 2006; Kemper et al., 2022; Kemper et al., 2023). Volumetric flow rates between 0.06 to 0.12 $m^3 s^{-1}$ are assumed to be necessary for replacing 0.5 to 1 cm d^{-1} of surface water within an area of one square kilometer by a single pipe (Koweek, 2022; Jürchott et al., 2023). Based on a replacement rate of 1 cm d^{-1}, achieving an upwelling rate of 1 Sverdrup (1 Sv = 10^6 $m^3 s^{-1}$) would require approximately 7 million pipes (Oschlies et al., 2010b). This ONET remains in early stages, with many uncertainties regarding undesired side-effects, its feasibility and maintenance costs. The CDR potential of AU assessed by model applications has been shown to be highly sensitive to the CO_2 emission scenarios considered (Jürchott et al., 2023). This sensitivity is mainly due to the fact that not only nutrients are pumped upwards, but also dissolved carbon, which can then outgas from the ocean into the atmosphere. Furthermore, the upward transport of cold and dense deep water causes warm surface waters to become mixed downwards, which is associated with a redistribution of heat with depth. Apart from these side-effects, AU could become a useful complementary option for cultivating and harvesting macroalgae (NASEM, 2020), as it would transport the nutrients required for growth to the farming areas.

Public perception

Artificial upwelling raises associations with offshore wind energy. Focus group participants questioned the technical feasibility of installing and maintaining large areas covered with pipes (Veland and Merk, 2021, **D3.3**), particularly under offshore conditions where corrosion, biofouling, and storm damage could increase costs and risks. They also worried about competition for ocean space, given existing pressures from shipping and the rapid expansion of offshore wind energy. Beyond these spatial conflicts, participants expressed concerns about unintended ecological impacts. While the aim is to stimulate primary production, large-scale changes in nutrient supply could lead to changes in plankton composition, which in turn could affect marine foodwebs. The idea that marine animals could become trapped in the pipes raises concerns about direct harm to wildlife. These concerns resonate with wider debates about ONET applications (Veland and Merk, 2021, **D3.3**; Andersen et al., 2022, **D3.4**).

Governance

The AU is not directly included in the scope of the London Convention and Protocol, as the definition of marine geoengineering includes "the placement of matter into the sea". The Convention on Biological Diversity (CBD) has the overarching objective to conserve biological diversity and, thereby, the framework has been deemed as implicitly relevant to the governance of potential unintended impacts of AU on marine biodiversity and ecosystems. In 2010, the CBD passed a decision to prohibit climate-related geoengineering "that may affect biodiversity, until there is an adequate scientific basis on which to justify such activities and appropriate consideration of the associated risks for the environment and biodiversity and associated social, economic and cultural impacts" (X/33 8(w)), with the exception of small-scale scientific research studies. The CBD defines climate-related geoengineering broadly as "deliberate intervention in the Earth's climate system that is intended to mitigate climate change or its impacts, excluding carbon dioxide removal technologies that address the causes of climate change directly" (Decision X/33), which applies to AU.

The application of AU has further been linked to potential negative effects on marine biodiversity, as the approach may generate enhanced phytoplankton production and substantially change species composition (Giraud et al., 2016). AU has also been linked to increased remineralization of organic material in the water column, which may increase methane and nitrous oxide release (Williamson et al., 2012). Therefore, AU may be implicitly governed by the CBD's objective to conserve marine biodiversity. While Decision X/33 is not legally binding and predates current marine CDR approaches, subsequent CBD decisions (most recently COP16 in 2024) have reaffirmed the relevance of the precautionary approach (i.e., taking preventive action in the face of scientific uncertainty) as well as principles of customary international law, such as the obligation not to cause transboundary environmental harm, for evaluating geoengineering activities.

Scalability & cost-efficiencies

The implementation of AU entails several cost components, which comprise expenses for pump materials, deployment, and energy consumption, as well as the establishment of offshore monitoring, reporting, and verification (MRV) programs. Additional costs arise from the operation of the pumps throughout their lifespan or their decommissioning at the end of their life cycles. According to estimates documented in NASEM (2022) and by Bednar et al. (2023), the total cost per ton of CO_2 sequestered ranges from $100 to $150, with the most significant expenditures attributed to sustaining a comprehensive MRV program. Prior to large-scale implementation, significant investments would be needed for additional field studies conducted over a ten-year period at multiple sites, with costs estimated at approximately $25 million per year (NASEM, 2022). While current commercial estimates suggest that an instrumented wave pump would cost around $60,000.

The initial CDR potential may be negative during the early years of AU before becoming positive (Yool et al., 2009). This negative period extends with the depth at which the pipes are deployed. Earlier simulation estimates approached a maximum CDR potential of around 3 $GtCO_2$ yr^{-1} (Oschlies et al., 2010; Keller et al., 2014). Assuming pipes that only reach down to 500 m, the estimate of the CDR potential can be much lower, around 0.05 $GtCO_2$ yr^{-1} (Koweek, 2022). By applying an algorithm that ensures that AU with pipes of 1000 m length is only active where the uptake of upwelled macronutrients is sufficiently large to avoid CO_2 outgassing, the estimates of CDR potential become larger again, between 1.2 $GtCO_2$ yr^{-1} and 3.7 $GtCO_2$ yr^{-1} for low and high emission scenarios respectively (Jürchott et al., 2023). Overall, the simulated CDR potential of AU is influenced by i) the large-scale redistribution of macronutrients such as nitrate and phosphate, ii) the pathway of future CO_2 emission, and also iii) the availability of iron as a micronutrient, which restricts the uptake of upwelled macronutrients (Jürchott et al., 2024).

Geochemical & ecological implications

Important insights into the effectiveness of AU and its potential impact on marine ecosystems can already be inferred from observational studies of natural upwelling systems (Bach and Boyd, 2021), where, for example, a relation between upwelling regions and the development of oxygen minimum zones is apparent. A further expansion of these naturally existing oxygen minimum zones is induced via AU in simulations of Jürchott et al. (2024). This, in turn, causes a net decline in the ocean's nitrate inventory, because of a disproportionately greater increase in denitrification compared to nitrogen fixation.

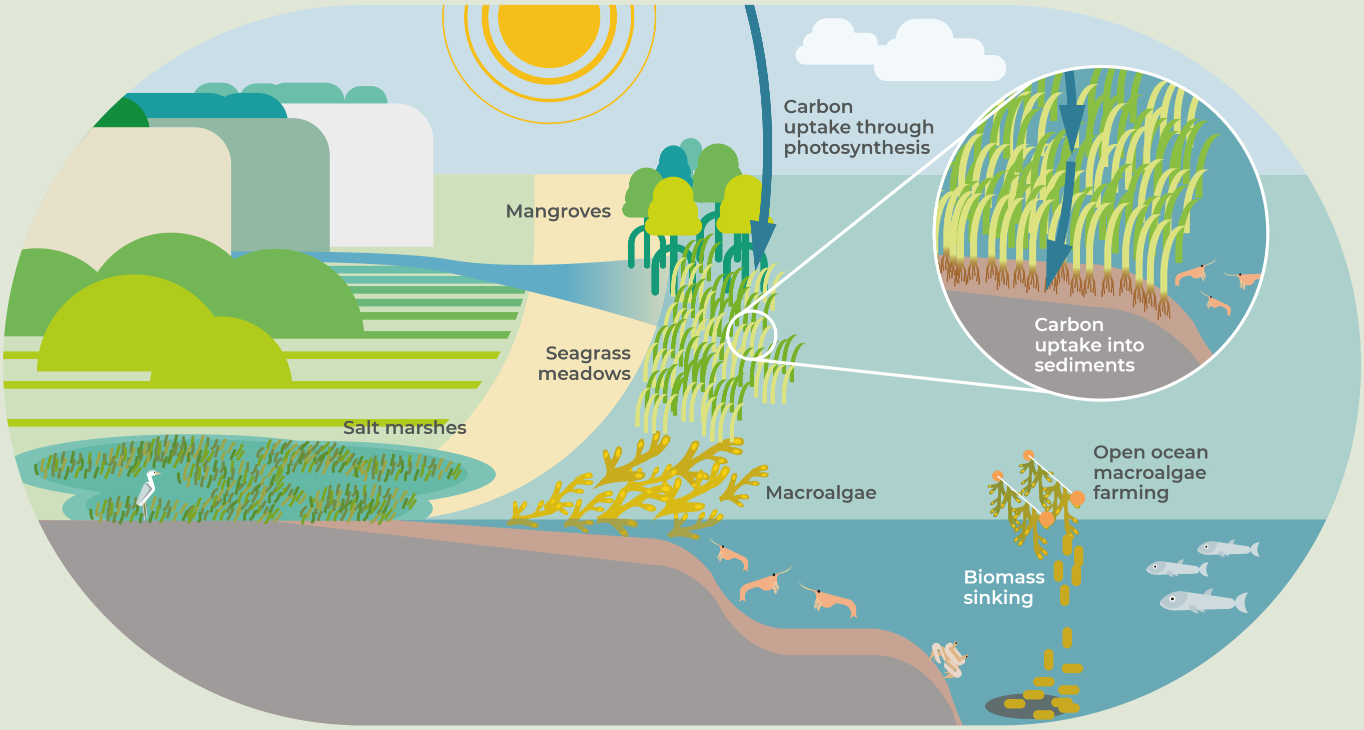
Another important side-effect of AU is the enhanced ocean heat uptake, caused by an increase of the temperature gradient between the surface ocean and atmosphere through the upwelling of cold water. If upwelling pipes are stopped, the heat stored in the ocean could be released back into the atmosphere, ultimately raising atmospheric temperatures compared to a scenario without artificial upwelling (Oschlies et al., 2010b). As with CDR potential, the side-effects of AU increase with both the length of the pipes, the intensity and duration of the upwelling.

Considerable CDR potential is to be expected in oligotrophic ocean regions where the surface layers of the ocean have naturally low productivity due to a persistent depletion of nutrients. Since these oligotrophic plankton ecosystems are highly adapted to some rapid and efficient recycling of nutrients, the influx of nutrients from AU may lead to changes in the composition of the phytoplankton community. Such compositional changes were observed in mesocosm experiments that simulated various AU intensities under pulsed, recurring conditions and for single influx events (Baumann et al., 2021; 2023; Goldenberg et al., 2024). In their studies the AU generally favoured the growth of silicifying algae (diatoms) that tend to be larger in size than the natural phytoplankton community. Intensified AU enhanced carbon uptake through increased nutrient supply. Yet, the resulting biomass exhibited elevated carbon-to-nitrogen ratios, which made the carbon-enriched diatoms a poor-quality food source for grazers such as copepod zooplankton (Goldenberg et al., 2024). Furthermore, the speed of the sinking (aggregated) biomass was reduced such that much of the additional organic carbon became rapidly remineralized and was not effectively exported. Although the biomass aggregates became larger, they sank more slowly due to the increased porosity of these carbon-enriched particle aggregates (Baumann et al., 2023).

COMPACT

Given the current state of knowledge, the practical, large-scale feasibility of AU as ONET remains unclear, with significant uncertainties in its adverse effects, as well as long-term maintenance costs. Although the build-up of biomass increases with AU, this would always be accompanied by changes in the community structure and biochemical composition of the plankton. AU may serve as a viable complementary approach for the cultivation and harvesting of macroalgae on regional scale.

Blue carbon



Blue carbon management is concerned with restoring and conserving coastal and marine ecosystems to enhance natural carbon storage. In contrast, macroalgae cultivation (farming) and harvesting produces biomass (seaweed) that can then be used for removing carbon either via sinking or through land-based BECCS. This latter blue carbon approach is considered distinct from habitat restoration and conservation. From an ONETs perspective, a tailored blue carbon management approach along coasts thus optimizes each ecosystem's carbon sequestration efficiency, while unintended environmental impacts are minimized. Natural coastal blue carbon ecosystems of focus include distinctive vegetated habitats such as mangrove forests, seagrass meadows and salt marshes (Duarte et al., 2005). With respect to coastal regions, blue carbon ecosystems, and the cultivation and harvesting of macroalgae, their uncertainties in their CDR potential as ONETs, have been further discussed in recent years (Williamson and Gattuso, 2022; Traeger and Balu, 2024; **D1.7**). Additional insights about scalability of coastal macroalgae aquacultures, in combination with subsequent biomass storage on land (marine BECCS), has been explored with an Earth System Model in Wu et al. (2024).

Under open ocean conditions, the macroalgae farming is very different from its coastal counterpart, with biomass eventually sinking to the ocean's bottom. Such an approach was considered in idealized model simulations, with or without additional artificial upwelling, providing global estimates of the scalability and biogeochemical side effects of such ONET (Wu et al., 2023). More specific open ocean estimates of the CDR efficiency were derived for *Sargassum* in the North Atlantic (Bach et al., 2021). Like for coastal blue carbon ecosystems, considerable uncertainties remain with regard to a credible CDR upscaling of open ocean macroalgae farming, and its potential role as a feasible ONET is still the subject of controversy (Wang et al., 2023; Smetacek et al., 2024).

Public perception

Coastal blue carbon management enjoys a positive image when it involves the restoration and conservation of ecosystems. This type of ONET is perceived to provide co-benefits for biodiversity and coastal protection, making it an appealing option for the public, stakeholders, and policymakers (Traeger and Balu, **D1.7**; Veland and Merk 2021; **D3.3**). Coastal ecosystem restoration is perceived as natural and a compensation of past harm done to the marine environment. Therefore, it is perceived substantially more positive than other ONETs despite the potential negative effects of large-scale interventions on local livelihoods and existing ecosystems that are replaced or potential conflicts between actors on international carbon markets and on the local level (Bertram and Merk, 2020; Merk et al., 2022;

Veland & Merk 2021, D3.3). The perception of macroalgae farming depends on the treatment of the biomass after the harvest. BECCS with marine biomass finds some support by the public, as summarized in Andersen et al. (2023, D3.6). While sinking the biomass in the deep-ocean is viewed as dumping, and as a risky and uncontrollable method. Public perceptions are rather negative in the Western countries surveyed while they are somewhat more positive in China and Taiwan (Merk et al., 2023, D3.5; Andersen et al., 2023, D3.6).

Governance

According to the categorization of Röschel and Neumann (2023), the governance framework for ONETs is positioned comparatively favourably towards coastal blue carbon management. The Convention on Biological Diversity (CBD) 2010 decision on biodiversity and climate change (X/33) encourages Parties to "implement ecosystem management activities, including the […] conservation of mangroves, salt marshes and seagrass beds […] as a contribution towards achieving and consistent with, the objectives of the United Nations Framework Convention on Climate Change, the United Nations Convention to Combat Desertification, the Ramsar Convention on Wetlands and the Convention on Biological Diversity." The UNFCCC 2013 Supplement to the IPCC Guidelines for National Greenhouse Gas Inventories on Wetlands provides guidance on management activities in coastal areas of mangroves, tidal marshes and seagrass meadows, while the REDD+ mechanism has further provided market funding for coastal blue carbon ecosystems. It can be concluded that the global framework for climate change is largely supportive of coastal blue carbon ecosystem restoration. The RAMSAR Convention on Wetlands Resolution (XIII.14) on promoting conservation, restoration and sustainable management of coastal blue-carbon ecosystems "encourages Contracting Parties that are in a position to do so, to substantially increase support, including financial support, to projects and research aimed at the conservation and protection of coastal blue-carbon ecosystems." The Convention for the Protection of the World Cultural and Natural Heritage (UNESCO) can be interpreted as implicitly supportive of coastal blue carbon restoration and management, as out of 50 marine sites on the UNESCO World Heritage List, 21 are specifically recognized for their coastal blue carbon ecosystems (Howard et al., UNESCO, 2014). As coastal blue carbon ecosystem restoration has been linked to positive spill-over effects for fisheries (Honda et al., 2013), the UN Fish Stocks Agreement has been suggested to have indirect relevance in regard to blue carbon activities. A 2024 ICES Workshop on "Anticipating the Impact of Marine Carbon Dioxide Removal (mCDR) on Fisheries and Aquaculture Species and Management" supports this assessment.

Scalability & cost-efficiencies

Coastal blue carbon ecosystem restoration is characterized by a high degree of technological readiness, a high degree of controllability at the local level (Gattuso et al., 2021; Babiker et al., 2022). For coastal blue carbon ecosystems, the overall CDR potential is generally low while uncertainties remain large, ranging from 0.06 to 2.1 $GtCO_2\ yr^{-1}$ (Williamson and Gattuso, 2022). These estimates correspond to 0.02 and 6.6 % of global CO_2 emissions in the year 2020 accordingly (Friedlingstein et al., 2022). The time scale for carbon storage of ONETs, such as coastal protection and restoration of mangroves, spans from decades to centuries. Griscom et al. (2017) found that some restoration efforts can be cost-effective at prices below \$100 per tCO_2, and could sequester between 0.6 and 1 $GtCO_2$ annually. Using blue carbon methods, Claes et al. (2022) found that about 0.4 to 1.0 $GtCO_2$ could be abated at costs less than \$18 per tCO_2. Average costs derived for coastal blue carbon measures may even range from \$10 to \$50 per tCO_2 (Bednar et al., 2023). Upscaled estimates of CDR potential and cost-efficiencies depend on carbon burial rates considered, which had been derived as arithmetic mean rates in some cases, despite the probability densities of the data being highly skewed and with geometric means being typically lower (Williamson and Gattuso, 2022). Similar to an illustration by NASEM (2022) with regard to scalability, it is instructive putting a burial rate of 500 $mgC\ m^{-2}\ d^{-1}$ (1.835 $gCO_2\ m^{-2}\ d^{-1}$, 670 $tCO_2\ km^{-2}\ yr^{-1}$) into a temporal and spatial perspective. To exploit the CDR potential of 0.1 $GtCO_2\ yr^{-1}$, a 200 m wide strip along a coastline of 746,519 km would then be required, which corresponds to about 46 % of the global coastline of length $1.63 \cdot 10^6$ km.

The protection of natural habitats of macroalgae together with their cultivation was reported to potentially sequester between 0.1 and 0.6 $GtCO_2\ yr^{-1}$ on global scale (Cross et al., 2023). The model simulations described in Wu et al. (2024) provide some hypothetical upper limit estimates of the CO_2 sequestration potential of nearshore macroalgae farming, if combined with carbon storage at land. Within the harvested ocean regions between 60° S and 60° N, the simulated unit-area CDR capacity depends on nearshore nutrient availability and varies between 107 and 171 tCO_2 km^{-2}, globally removing between 2.6 and 4.0 $GtCO_2$ yr^{-1}. Corresponding cost estimates vary widely (see above). While Cross et al. (2023) report costs below 100 USD/tCO_2, Froehlich et al. (2019) mention considerable regional variations of costs due to different cultivation and harvest designs, as well as regional disparities in labor costs and their analysis suggests that initial costs could far exceed 100 USD/tCO_2.

The area potentially suited for open ocean macroalgae growth and sinking of biomass varies between seasons, depending on nutrient and light availability. Specific requirements for macroalgae open-ocean culturing were imposed in the idealised global model simulations of Wu et al. (2023). In the absence of artificial upwelling such cultivation area would encompass 70 · 10^6 km^2 (19 % of total ocean area), with a carbon sequestration potential of around 12 $GtCO_2$ yr^{-1} within the first 80 years of deployment. With artificial upwelling added, the area expands to 130 · 10^6 km^2 (36 % of the total ocean area), further enhancing the CDR potential up to 20 $GtCO_2$ yr^{-1}. Despite such high CDR potential under the RCP 4.5 moderate-mitigation scenario considered in Wu et al. (2023), the macroalgae culturing and sinking at a maximum possible scale alone would be insufficient to keep global warming below 2 °C by the year 2100.

Geochemical & ecological implications

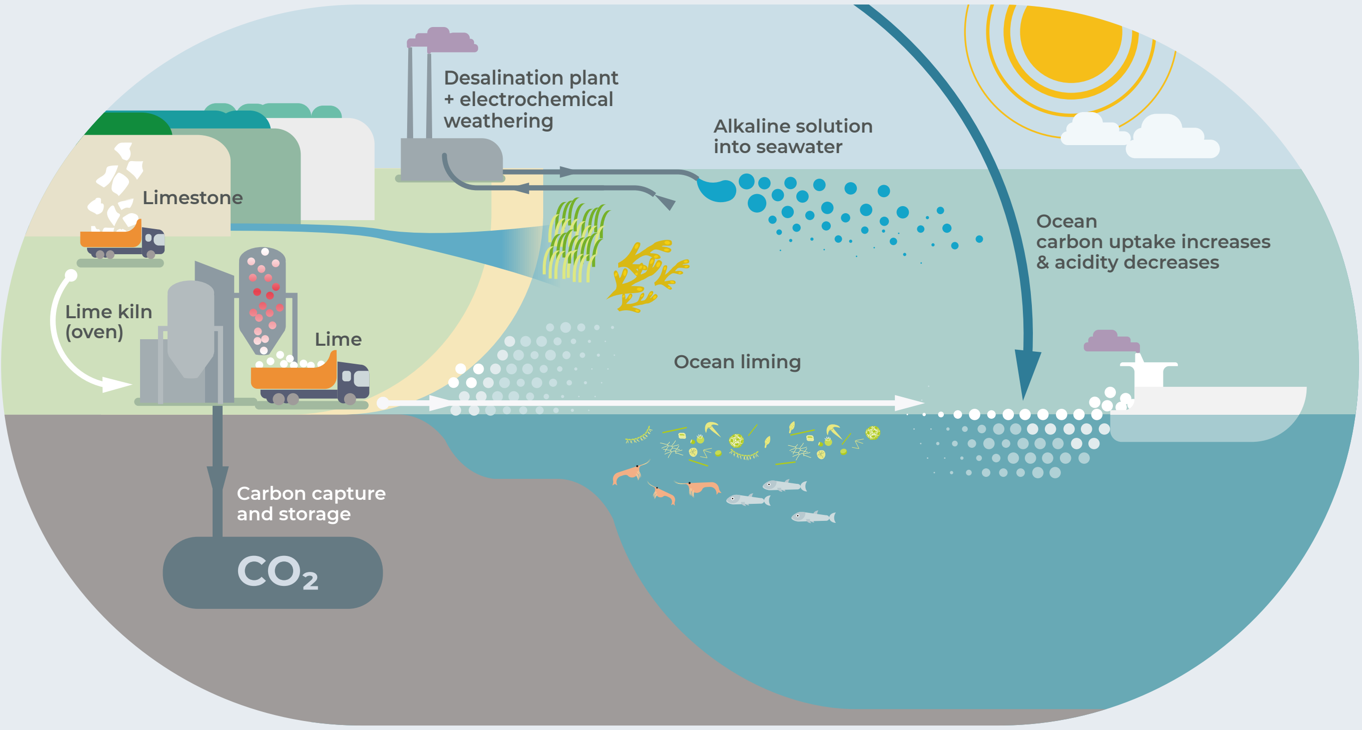
The restoration and protection of coastal blue carbon ecosystems likely improves nearshore environmental conditions, which provides ecological benefits. Although these coastal vegetated habitats' potential for CDR is low on global scale, their advantages should be appreciated on a regional level. Additional monitoring of greenhouse gas emissions of methane and nitrous oxide is recommended, in particular during periods of restoration (Williamson and Gattuso, 2022).

The cultivation and harvesting of macroalgae along coastlines will likely be associated with changes of the surrounding landscape, including transportation pathways. The overall environmental impact is expected to be low, provided that all biomass can be well captured, transported and safely buried (stored). In contrast, large-scale open-ocean cultivation of macroalgae and their intentional sinking are expected to induce substantial biogeochemical changes. Model simulations by Wu et al. (2023) indicated a projected 37 % decline in net primary production. Their model results exemplify the relative shift in the build-up of biomass away from small plankton cells to macroalgae, which introduces a redistribution of carbon biomass, risking the negative side effect of expanding benthic oxygen minimum zones.

COMPACT

The scalability and side effects of blue carbon strategies differ substantially, depending on which ONET option is considered. The restoration and conservation of coastal and marine ecosystems usually have a very low CDR potential, with correspondingly appreciated co-benefits, while there are no or low negative side effects. Open-ocean macroalgae cultivation may actually require additional measures for nutrient supply, such as AU, and must also cover large ocean areas in order to achieve significant negative emissions. The associated negative effects are known and their extent, if applied on regional scale, must be considered and should be monitored accordingly.

Ocean alkalinity enhancement



Ocean alkalinity enhancement (OAE) has been proposed as a marine CDR technique that would increase the ocean's capacity to store carbon. In contrast to many other gases, CO_2 does not only dissolve in seawater, but it also acts as a weak acid that reacts with water to form free protons (H^+), as well as bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions. Since atmospheric CO_2 equilibrates solely with the dissolved aqueous CO_2, and not with HCO_3^- or CO_3^{2-}, the ocean holds much more carbon than predicted by the solubility of CO_2. The partitioning of the oceanic pool of dissolved inorganic carbon (DIC) into its constituents (CO_2, HCO_3, and CO_3^{2-}) is governed by the total alkalinity (TA) and the pH of seawater, where TA is defined as the capacity of seawater to neutralize an acid. An increase in TA shifts the equilibrium of the seawater CO_2 system towards more HCO_3^- and CO_3^{2-} ions, decreases the concentration of dissolved CO_2, and consequently leads to an uptake of CO_2 from the atmosphere. Due to the ocean's large size, small relative changes in TA could sequester a large proportion of anthropogenic carbon, such that artificial OAE is seen as one of the ONETs with high theoretical potential for CDR. In terms of scalability, potentially feasible scenarios can best be derived if existing industrial infrastructure and capacities are taken into account. This is particularly possible with regard to the existing cement industry for the application of ocean liming (OL), as well as existing desalinization plants for the application of electrochemical brine splitting (EBS). The OAE induced shift of DIC in seawater away from CO_2 towards carbonate can affect plankton growth conditions and will potentially change the activity of enzymes produced by bacteria due the associated increase in pH. So far, impacts have been assessed with respect to the plankton community as well as the early life stages of higher trophic levels.

Public perception

In the three studies conducted within OceanNETs, the support was lowest for OAE and it was perceived as "risky" and "costly". The sinking of biomass in the ocean was the only option regarded as comparable, and it was more often described as "uncontrollable" (Merk et al., 2023, **D3.5**). In discussions about OAE, participants tended to talk about broader issues such as the importance of tackling the causes of climate change, i.e., CO_2 emissions, rather than the symptoms, i.e., carbon removal. Participants were concerned, on the one hand, that additional mining and industrial infrastructure would be necessary, and on the other hand, that adding alkalinity would mean introducing further chemicals into the marine environment, which was often equated with (plastic) pollution. This perception changed when OAE was framed as an extension of existing interventions, such as its integration with a desalination plant (Veland and Merk, 2021, **D3.3**; Andersen et al., 2023, **D3.4**).

The cross-country survey revealed that presentation order influenced participants' evaluations. Specifically, introducing

OAE first produced a negative halo effect on the assessment of subsequent NET options, including marine BECCS. In perspective, perceptions of biomass sinking were not affected by presentation order and showed no comparable negative halo effect (Merk et al., 2023, **D3.5**). While OAE was perceived most positively in China, more skeptical views emerged in Taiwan, highlighting a difference between the two Asian countries that was not observed for other methods or topics in the comparative survey. Among Western countries, participants from France and Germany were the most skeptical, although the gap compared to Canada and Norway was relatively small. Overall, it was found that greater openness to innovation and technology was always accompanied by a more positive perception of the methods.

Governance

Nawaz et al. (2023) recommend a nuanced approach that allows for flexible local governance of marine CDR, including OAE options like OL, coastal enhanced weathering or the use of existing waste desalination brines for EBS. Given the complexity and uncertainties involved, climate mitigation efforts are often more effective and equitable when managed at the local scale, where ecological, social, and regulatory contexts can be directly addressed. At the same time, international agreements provide overarching guardrails that constrain and guide local decision-making. For example, the London Protocol's (not yet in force) Amendment to Article 6bis on marine geoengineering activities mandates that "Contracting Parties shall not allow the placement of matter into the sea from vessels, aircraft, platforms or other man-made structures at sea for marine geoengineering activities listed in annex 4." This illustrates the need for local governance to remain flexible while still converging with and adhering to international norms.

Nawaz et al., (2023) recommend a nuanced approach that allows for flexible local governance of marine CDR, such as OL, coastal enhanced weathering, or the use of existing waste desalination brines for EBS. Given the complexity and uncertainties, effective and equitable climate mitigation efforts are ultimately better managed on local scale, where ecological, social and regulatory contexts can be directly accounted for. At the same time, international agreements provide overarching guardrails that constrain and guide local decision-making. For instance, the London Protocol's (not yet in force) Amendment to Article 6bis on marine geoengineering activities mandates that "Contracting Parties shall not allow the placement of matter into the sea from vessels, aircraft, platforms or other man-made structures at sea for marine geoengineering activities listed in annex 4". While ocean fertilization is currently the only activity listed in Annex 4, OAE is being reviewed as one of four additional ONETs potentially to be included under this international framework. For OAE, this highlights the need for coordination, ensuring that local governance remains flexible while still aligning with international norms.

Scalability & cost-efficiency

To achieve gigatonne-scale CDR, OAE requires massive logistical operations. The scalability of OAE is therefore likely to be limited either by the supply chain of alkalinity to the ocean, and/or the environmental burden around the point of addition. In case of OL, for example, the existing natural resources of rocks containing carbonate and silicate minerals have the potential of sequestering thousands of Gt of CO_2 (Bach et al., 2019). In practice, restrictions are rather associated with the infrastructure for comminution of e.g. limestone as well as for its further processing (e.g., calcination) and the dispersal in the ocean. Therefore, considering the existing industrial infrastructure and capacities, reasonable estimates of scalability of OAE are achievable for OL and EBS, as well as for CEW (Campbell et al., 2024, **D6.6**). The main component technologies are regarded as mature (technology readiness level, "TRL", 9). When governance, policy, and public acceptability for OL are also mature, the existing component technologies could support its direct scaling up. If policy was to support large scale OAE it might be feasible to have such permit within 5 years or less, while a new mining permission requires around 3 years (Mineral Products Association, 2021). Regarding the expansion of infrastructure for mineral extraction and processing, planning a new cement plant is estimated to take 8–10 years, while construction requires roughly 2 years (Bliss et al., 2008). Ideally, the steps for obtaining a mining permit could always be coordinated in parallel with the implementation of construction planning and measures, for e.g. calciners and CCS, which may reduce the overall timeframe to 5 years or less. The use of desalination brines for electrochemical alkalinity production will likely take several more years before reaching maturity.

Historical data about the utilization capacities of the mining, the cement, and the lime industries were collected, analysed and modelled (Foteinis and Renforth, 2021, **D6.2**). By doing so the spare capacities of these industries were identified and these were used to derive future projections (scenarios) of OL for Europe, China and the USA. While also considering the expansion of infrastructure for mineral extraction and processing, a very optimistic scenario for the starting date of OAE at scale was found to be in 2030. These projections were applied as realistic coastal deployment scenarios in an ensemble of simulations of multiple Earth System Models (ESM)s. On global scale, and according to the mean of ensemble solutions described in Sathyanadh et al. (2025, submitted & **D4.6** and **D4.9**), the CDR potential ranges between 12.4 and 16.0 $GtCO_2$ yr^{-1} within the first decade when OAE starts (2030 – 2040). During the last decade (2090 – 2100) the annual CDR reduces to 1.7 - 3.0 $GtCO_2$ yr^{-1}. The cumulative CDR reaches a total of 659 $GtCO_2$ by 2100.

Given that Spain has the capacity to implement OL and EBS together with some CEW, a combination of these ONETs could be assessed. In case of all three ONETs being implemented on regional scale, Spain has a CDR potential of 25 $MtCO_2$ yr^{-1} (OL = 23 $MtCO_2$ yr^{-1} and EBS = 2 $MtCO_2$ yr^{-1} respectively; Campbell et al., 2023, **D6.4**) and an additional 1 $MtCO_2$ yr^{-1} for CEW (Foteinis et al., 2025, submitted). In a regional model application of ship-based OL near the Canary Islands, and by utilizing only 0.4 % of the projected total OL capacity for Europe, the CDR potential ranges from 1.5 to 2.2 $MtCO_2$ yr^{-1} by 2100, with efficiencies between 0.65 and 0.95 tCO_2 per $tCa(OH)_2$ deployed, depending on the CO_2 emission pathway scenarios (Schartau et al., 2024, **D5.8**).

Variations in OAE efficiencies due to the assumed emission pathway are documented in Schwinger et al. (2024), being larger at locations and during periods where the surface concentration of DIC is high. The efficiency of OAE for CDR thus depends on the state of the seawater carbonate chemistry. The study of Hinrichs et al. (2023) implies that a correct representation of alkalinity and DIC fields in models is critical for assessing the efficiencies correctly. Because most CMIP6 models currently overestimate OAE-induced CO_2 drawdown due to biases in their alkalinity and DIC fields, greater emphasis should be placed on reducing these biases. Also, parallel high and standard resolution OAE experiments indicate that an improved representation of small-scale features of the ocean circulation tends to reveal a lower efficiency of OAE, presumably by reducing the surface residence-time of the added alkalinity (Keller et al., 2023, **D4.3**).

First detailed evaluations of cost-efficienies were derived for OL, clarifying that primary expenses are related to energy and fixed operational costs (Renforth et al., 2013). This is also reflected in the cost calculation in van Kooten et al. (2023, **D1.4**). With CCS included, the cost estimates are typically above 200 USD/tCO_2, 267 ± 41 USD/tCO_2 according to Renforth et al. (2013). By considering additional techno-economic aspects, more recent estimates are 133 to 296 USD/tCO_2, when natural gas or electricity are needed to generate the heat for calcination (Kowalczyk etal., 2024). These costs may further increase, as long as ship-based deployment still relies on fossil fuels, ranging between 156 and 380 USD/tCO_2. For OAE with sodium hydroxide derived from desalination waste brines, the cost efficiency lies between ~300 and more than 1000 USD/tCO_2, based on some elaborate life cycle assessment of applying bipolar membrane electrodialysis method (Pereira et al., 2025). In their case study, again the costs for electricity are the highest, while the electrodialysis process itself reveals the greatest potential for cost reductions.

Geochemical & ecological implications

Multi-model simulations of realistic coastal OL scenarios show that the model agreement on the CDR removed by the OAE intervention is relatively good. The results indicate that atmospheric CO_2 can be lowered by 8 ppm, with an inter-model range of 7 - 9 ppm (Sathyanadh et al., 2025, submitted & **D4.6** and **D4.9**). These multi-model simulations were emission-driven and do resolve fluxes of CO_2 from the land and ocean back to the atmosphere in response to lower atmospheric CO_2 concentration. Despite the considerable CDR (659 $GtCO_2$ by 2100), the resulting temperature response, however, is too small to be distinguished in any of the models from natural variability.

Mesocosm experiments under CO_2-equilibrated conditions of OAE did not disclose any significant detectable responses in phytoplankton productivity under low nutrient conditions (Paul et al., 2025), and meso-zooplankton turned out to be fairly resilient under these conditions (Sanchez et al., 2024). Fish were not only found to tolerate OAE, but may have even benefitted, as suggested by the increased fish biomass with increasing alkalinity. The mechanisms behind such a co-benefit could not be resolved. Impacts on nutrient utilisation and particulate matter production and stoichiometry (carbon-to-nitrogen ratio) were found to be minor (Marín-Samper et al., 2024a; Suessle et al., 2025). Xin et al. (2024b) document that the phytoplankton communities maintained their natural biomass and size structure. However, details with regard to microbial dynamics, e.g. the interdependencies between bacteria and small sized pico- and nano-plankton, remain unclear. Under oligotrophic conditions, and based on samples from the North Atlantic Subtropical Gyre, the analyses of particle size spectra indicate shifts in plankton composition in response to OAE (Subhas et al., 2022), which deserves further attention with regard to the underlying mechanisms.

Experiments, including mesocosm studies, of OAE under unequilibrated conditions revealed changes in growth rates and resolved differences in the plankton composition to additions of olivine/silicate-based (Mg_2SiO_4) versus calcium-based ($CaCO_3$) minerals (Kittu and Riebesell, 2025, **D5.7**). The responses seen and their underlying non-linear ecosystem dynamics appear complex. Overall, their findings stress that the environmental conditions prior to OAE, in particular the nutrient availability (repletion vs depletion), determine the strength of the response. Ultimately, the pre-conditioning, timing and location, of alkalinity deployment need to be accounted for.

ESM simulations that describe the effects of changes in the carbonate system on phytoplankton growth and calcification suggest that the direct effect of OAE on growth and calcification is small (Seifert et al., 2025). However, such small changes may scale up through gentle shifts in the competition for nutrients and light as well as in grazing pressure (Seifert et al., 2022), indirectly leading to decreasing phytoplankton productivity in regions of OAE (Seifert et al., 2025). Furthermore, their model analysis shows that biological responses to OAE can modify the OAE efficiency, potentially complicating the estimation of OAE-induced atmospheric CO_2 drawdown in real world OAE applications.

The local simulations near the Canary Islands of Schartau et al. (2024, **D5.8**) yield short-term decline in phytoplankton biomass by approximately 15 % (along with 6 % reduction in bacteria, and only 1.5 % in zooplankton), in response to repeated (annual) instant perturbations induced by OAE. Reductions in net primary production rates of similar scale, by up to 20 %, are obtained by Seifert et al. (2025) only within the near-shore deployment regions of China where the highest intensity of OAE was imposed. When taking into account viable intensities of OAE and considering pulsed, ship-based deployment of calcium hydroxide within an oligotrophic region, the extent of the reduction in the build-up of plankton biomass is less than 20 % relative to undisturbed growth (negative anomaly), followed by a subsequent increase of biomass (temporally shifted positive anomaly) (Schartau et al., 2024, **D5.8**). Horizontal dispersal of local alkalinity, e.g. ship-based, alkalinity addition essentially reduces impacts on a wider regional scale (Caserini et al., 2021), while such OAE remains an effective CDR measure. OAE is likely to have minimal impact on plankton dynamics within oligotrophic regions, where maxima in primary production and thus major build-up of biomass are found at depths around 100 m, well below the upper stratified 10 to 30 m that would be subject to perturbations introduced via e.g. ship-based OAE.

To better understand the long-term effects of OAE on marine ecosystems, existing analogs in which elevated alkalinity conditions prevail can be used for further investigations in the field, like the Black and Caspian Seas (Bach and Boyd, 2021). For enhancing our knowledge about biogeochemistry of OAE, its CDR potential and side effects, model applications are indispensable (Fennel et al., 2023), not to mention their role for resolving aspects of monitoring, reporting and verification of OAE.

COMPACT

The application of OAE as an ONET is critically viewed by the public and regulations for how OAE could be treated in the London Convention and Protocol remain unclear. At the same time, studies have shown that OAE is one of the most efficient ONETs,, which has the potential to become more cost effective in the future while keeping its CO_2 footprint low. For OL and EBS substantial new knowledge has been gained from in-depth life cycle assessments. These analyses and assessments reveal viable pathways by building on and expanding existing infrastructure, like the cement industry and desalination plants. The impact of OAE on the ecosystem is rather short-termed and the level of perturbation can be kept low. Applications of ship-based OAE are likely to have very minor effects at oligotrophic ocean sites where biomass and nutrient concentrations are very low. The maximum intensity and best timing of OAEs vary by region, so future studies that are more tailored to specific marine areas could provide more insight. Comprehensive assessments of OAE that consider site-specific environmental, social and political factors can therefore help to reveal detailed practical challenges and explore public engagement strategies.

Acronyms

ASR	Articles on States Responsibility
BECCS	Bioenergy with Carbon Capture and Storage
BSi	Biogenic Silica
$CaCO_3$	Calcium carbonate
CaO	Calcium Oxide (quicklime)
$Ca(OH)_2$	Calcium Hydroxide (slaked lime)
CBD	Convention on Biological Diversity
CCS	Carbon capture and Storage
CDR	Carbon Dioxide Removal
CEW	Coastal Enhanced Weathering
CGE	Computable General Equilibrium model
CLM	Community Land Model
CMS	Convention on the Conservation of Migratory Species of Wild Animals
C:N	Carbon to nitrogen ratio
CO_2	Carbon dioxide
CS	Cross-country survey
CMIP6/7	Coupled Model Intercomparison Project phase 6/7
CO_3^{2-}	Carbonate
D	Deliverable
DART	Dynamic computable general equilibrium model
DCR	Direct Carbon removal from Seawater
DIC	Dissolved Inorganic Carbon
DMP	Data Management Plan
DOI	Digital Object Identifier
DS	Deliberative survey
DTA	Delta total alkalinity
ESR	Effort-Sharing-Regulation
ESTOC	European Station for Time-Series in the Ocean of the Canary Islands
FAOSTAT	Food and Agriculture Organization of the United Nations Statistical Database
FG	Focus groups
FOCI	Flexible Ocean and Climate Infrastructure (high resolution nested model)
EBS	Electrochemical brine splitting
EEZ	Exclusive Economic Zones
EMIC	Earth system Model of Intermediate Complexity
ESM	Earth System Model
ETS	Emission Trading System
FAIR	Findability, Accessibility, Interoperability, and Reuse of digital assets
FaIR	Finite amplitude Impulse Response model
GLODAP	Global Ocean Data Analysis Project
GP	Gross production
HCO_3^-	Hydrogencarbonate (bicarbonate)
IAM	Integrated Assessments Model
IGO	Intergovernmental Organisations
ILC	International Law Commission
ISAB	International Scientific Advisory Board

LCA	Life Cycle Assessment
LC/LP	London Convention and Protocol
MAC	Marginal Abatement Costs
mBECCS	Marine bioenergy with Carbon Capture and Storage
NCP	Net Community Production
NETs	Negative Emission Technologies
NGO	Non-governmental organization
NPP	Net Primary Productivity
NCP	Net Community Production
NEGEM	Negative Emission project funded by the EU Horizon 2020 Programme, assessing realistic potential of negative emission technologies and practices
NorESM	Norwegian Earth System Model
NZ	New Zealand
OAE	Ocean Alkalinity Enhancement
OL	Ocean Liming
ONET	Ocean-based Negative Emission Technology
OPPLA	Optimality-based Plankton Ecosystem Model
OSIS	Ocean Science Information System
pCO_2	partial pressure of CO_2
PEDR	Plan for Exploitation and Dissemination of Results
PP	Primary production
PPE	Perturbed Parameter Ensemble
RDMO	Research Data Management Organiser
RRI	Responsible Research and Innovation
SDG	UN Sustainable Development Goals
SRG	Stakeholder Reference Group
SSP	Shared Socioeconomic Pathway
SO	Specific Objectives
SODP	Stanford Online Deliberative Platform
TA	Total Alkalinity
UNCLOS	United Nations Convention on the Law of the Sea
UNESCO	Convention for the Protection of the World Cultural and Natural Heritage
UNFCCC	United Nations Framework Convention on Climate Change
VTT	Technical Research Centre of Finland Ltd

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