Exploring site-specific carbon dioxide removal options with storage or sequestration in the marine environment - The 10 Mt CO2 yr-1 removal challenge for Germany

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Abstract

Marine carbon dioxide removal (mCDR) and geological carbon storage in the marine environment (mCS) promise to contribute to the mitigation of global climate change in combination with drastic emission reductions. However, the implementable potential of mCDR and mCS depends, apart from technology readiness, also on site-specific conditions.

In this paper, we explore different options for mCDR and mCS, using the German context as a case study. We challenge each option to remove 10 Mt CO2 yr-1, which accounts for 8-22% of projected hard-to-abate and residual emissions of Germany in 2045. We focus on the environmental, resource, and infrastructure requirements of individual mCDR and mCS options at a specific site, within the German jurisdiction when possible. Furthermore, we discuss main uncertainty factors and research needs, and, where possible, cost estimates, expected environmental effects, and monitoring approaches.

In total, we describe ten mCDR and mCS options; four aim at enhancing the chemical carbon uptake of the ocean through alkalinity enhancement, four aim at enhancing blue carbon ecosystems' sink capacity, and two employ geological off-shore storage. Our results indicate that five out of ten options would potentially be implementable within German jurisdiction, and three of them could potentially rise to the challenge. This exercise provides a basis for further studies to assess the socio-economic, ethical, political, and legal aspects for such implementations.

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Exploring site-specific carbon dioxide removal options with storage or sequestration in the marine environment - The 10 Mt CO_2 yr^{-1} removal challenge for Germany

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Key Points:

- The site-specific context of carbon dioxide removal options is crucial for serious considerations regarding their possible implementation.
- Marine carbon dioxide removal options in Germany have the potential to contribute to counterbalancing of projected future residual emissions.
- Further site-specific studies are needed to include and assess the socio-economic, legal, political and ethical aspects for such implementations.

Abstract

Marine carbon dioxide removal (mCDR) and geological carbon storage in the marine environment (mCS) promise to contribute to the mitigation of global climate change in combination with drastic emission reductions. However, the implementable potential of mCDR and mCS depends, apart from technology readiness, also on site-specific conditions.

In this paper, we explore different options for mCDR and mCS, using the German context as a case study. We challenge each option to remove 10 Mt CO_2 yr^{-1}, which accounts for 8-22% of projected hard-to-abate and residual emissions of Germany in 2045. We focus on the environmental, resource, and infrastructure requirements of individual mCDR and mCS options at a specific site, within the German jurisdiction when possible. Furthermore, we discuss main uncertainty factors and research needs, and, where possible, cost estimates, expected environmental effects, and monitoring approaches.

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Plain Language Summary

There is a growing consensus within the scientific community that carbon dioxide removal (CDR) and carbon storage will play crucial roles in global climate change mitigation efforts. Marine-based CDR(mCDR) or carbon storage(mCS) for climate mitigation have gathered significant attention due to their substantial global potential.

While numerous studies have assessed global CDR capacities and associated side-effects or co-benefits of individual methods, it is important to recognize that global potential does not necessarily translate into local effectiveness. The implementable potential of mCDR and mCS depends not only on technological readiness, but also on site-specific conditions. Therefore, our study explores marine-based methods capacities considering local resource availability, geophysical conditions, infrastructure, and land/sea-area availability to be developed by Germany. We identified 10 proposed options, with half of them being implementable exclusively within German jurisdictions and 3 capable of achieving the 10 Mt CO2 annual removal target, significantly contributing to Germany's Net-Zero goal. This underscores the critical importance of considering site-specific contexts in any discussion of mCDR/mCS implementation. Additionally, our study highlights the potential of mCDR/mCS for Germany and calls for further site-specific studies to assess these options beyond natural science or techno-environmental considerations.

1 Introduction

The Paris Agreement (UNFCCC, 2016) requires achieving a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century. Such a net-zero goal first and foremost requires substantial reductions and avoidances in greenhouse gas (GHG) emissions. In addition to drastically reducing current emissions, the implementation of carbon dioxide removal (CDR) approaches will play a role in achieving net-zero by counterbalancing residual emissions (i.e. where emission reduction is technologically and/or financially too challenging; Buylova et al., 2021; Fridahl et al., 2020; Mengis et al., 2022; Oschlies et al., 2017). The sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2023) shows that all 1.5°C scenarios applied CDR to reach their goal. However, the CDR options implemented in the scenarios depend, among others, on assumptions that could reasonably be made about cost-effectiveness and storage availability of CO_2 (IPCC, 2022). Until now, most considered CDR methods are land-based, relying primarily on afforestation as well as bioenergy in combination with carbon capture and storage (BECCS). Most of the CDR options mentioned in national long-term low-emission development strategies worldwide rely on the expansion or management of existing natural ecosystem sink capacities (Thoni et al., 2020). Accordingly, a considerable amount of research has been devoted to these CDR options, which has resulted in first considerations of limiting factors or bottlenecks. For instance, large-scale, land-based CDR options relying on photosynthetic carbon capture require substantial land area, compete with other land uses such as food, fiber, and energy production, settlement and infrastructure development, and ecosystem services (Boysen et al., 2017; Fujimori et al., 2022; Williamson, 2016). While it is expected that large-scale implementation of any CDR option faces limitations, risks, and biophysical, technical, political and social challenges (Creutzig et al., 2015; Fuss et al., 2018), assessments of mCDR and mCS approaches within a portfolio of CDR options to reach net-zero emissions are lacking. This omission of marine approaches is a shortcoming, given the high carbon storage inventory of the marine environment and the large fraction of anthropogenic CO_2 that will finally be stored by the ocean.

Germany has set its goal to become GHG neutral by 2045. Optimistic roadmaps to reach this goal provide estimates of residual emissions ranging from 40 to 60 megatons (Mt) carbon dioxide equivalent (CO_{2eq}) annually (Federal Climate Change Act, 2019; Mengis et al., 2022), which corresponds to 5-10% of Germany's current GHG emissions. These will need to be counterbalanced by the implementation of CDR methods. Less optimistic annual residual GHG emission estimates are even higher, ranging from 45-130 Mt CO_{2eq} (Luderer et al., 2021; Merfort et al., 2023). Initial studies of CDR potential within Germany point to a theoretical CDR potential that could reach this scale by employing terrestrial CDR options (Borchers et al., 2022; Merfort et al., 2023). However, if the assumptions made about land, fresh water and energy requirements, as well as storage capacities, cannot be met without exceeding environmental guard rails, this could reduce the CDR potential (Heck et al., 2018).

Here, we aim to complement such efforts by considering the potential of CDR options with storage or sequestration in the marine environment for Germany. To do so, we envision potential implementations of different marine CDR (mCDR) categories: i) the enhancement of the ocean's chemical carbon uptake through alkalinity addition, ii) the enhancement of the "blue carbon" sink capacity (such as in salt marshes, seaweed, or mangrove ecosystems), and iii) off-shore geological CO_2 storage coupled with different carbon capture components. We challenge each mCDR option to reach a 10 Mt CO_2 yr^{-1} removal capacity, as this is a significant fraction of the residual emissions projected for Germany and allows us to assess side-effects and challenges, which are likely to be notable on that scale. In addition, by leveling the playing field for all options, we can compare common attributes of the aforementioned mCDR options at the same scale of operation. Our exercise does not aim to provide a comprehensive assessment of mCDR options, but rather a collection of options that can serve as the basis for further discussion by making the scale of CDR implementation relevant for national climate targets more tangible.

To this end, we aim to provide first insights into mCDR options on a larger scale, their technological feasibility, infrastructure and resource demands, on the example scale under the site-specific constraints. We first describe how we selected the mCDR and mCS options (section 2). We then provide a short description of each option, including technological readiness, resource requirements, uncertainties and, if available, cost estimates (section 3). This is followed by a comparison of the options, expected possible environmental effects, and a discussion of the limitations of our approach (section 4). Finally, we conclude that mCDR options are a valuable addition to the net-zero tool box, and that further research is needed to help some of the technology to reach maturity and to reduce the uncertainty in environmental effects.

2 Materials and Methods

2.1 CDR options development

Following the methodological approach presented by Borchers et al (2022) with experts from the CDRmare (cdrmare.de) research program, we developed a collection of possible mCDR options for implementation in Germany (Figure 1B). These mCDR options were generated based on three CDR methods researched in the program: ocean alkalinity enhancement (OAE), blue carbon enhancement (blueCDR), and off-shore geological carbon storage (mCS) captured from the atmosphere, e.g., through bioenergy plants or direct air capture, in collaboration with the research mission CDRterra (cdrterra.de).

The aim was to identify site-specific mCDR options, if possible within the German jurisdiction, yet, due to option specific geophysical constraints, some mCDR options are partially (e.g., basalt CO_2 trapping) or entirely (e.g. Mangrove planting) located outside of it. Such options would require international cooperation as outlined in Article 6 of the Paris Agreement (UNFCCC, 2015). However, how it would be ensured that these option implementations deliver on promoting sustainable development and environmental integrity warrants further consideration (see section 4.2, for some deliberation).

This study will describe necessary conditions for each option implementation, including environmental conditions, infrastructure, and technology and resource availability, as well as possible environmental effects. The options were created using a tabular fact sheet, adapted from Borchers et al. (2022), with a unified set of categories and parameters (see Table 1).

At this point, the implementation of OAE, blueCDR and mCS options were envisioned disregarding economic (beyond cost), legal, societal, or political constraints (similar to Borchers et al., 2022), and assuming - where no other information was available - linear scalability to 10 Mt CO_2 removal potentials. The locations in Germany for resource extraction, material processing, and establishment of logistics centers were chosen based solely on resource and infrastructure availability, which were only used to provide a basis for estimates such as transportation requirements, energy demands, and operational costs. This approach allowed us to fully explore techno-environmental feasibility and operational locations, necessary infrastructure, and resources under idealized, hypothetical conditions. Although we outline and discuss limitations arising from these assumptions in the overarching discussion, we recommend a detailed assessment of these disregarded factors as the subject of a follow-up study.

Table 1. Description of the categories and parameters used in the fact sheet for the generation of mCDR options with the aim to reach 10 Mt CO_2 yr^{-1} removal; for details see Supporting Information (SI).

Category	**Parameter**	**Description**
Option description	Maturity level	Extent to which an option is available for implementation, following the Technology Readiness Level (TRL) scale (European Commission, 2014). (See SI Table S2)
	Infrastructure	Necessary infrastructure along the chain of implementation.
	Biophysical conditions	Necessary environmental conditions for the functioning of the option.
	Location	Description of the possible locations and explanation for specific choice made, including the location for resource extraction, material processing, logistic centers, and carbon reservoir.
Demand/Input	Area/land	Necessary amount of area on land or ocean.
	Material/resources	Necessary amount and type of matter (e.g., rock, soil, etc).
	Energy demand	Energy demand along the chain of implementation
	Water demand	Necessary amount and type of water.
Output	CO_2 removal potential	If the option cannot reach 10 Mt CO_2 yr^{-1} removal, estimate the maximum yearly CO_2 removal rate.
	By-products	Additional products with or without market value generated.
	Energy output	Energy provision in the form of usable electricity/heat.
Environmental impacts	Soils/sediment	Effect of the option causing changes in the state of soils/sediments (e.g., through substance release).
	Water	Effect of the option causing changes in the state of groundwater, runoff water and seawater (e.g., through substance release).
	Air	Effect of the option on the atmosphere (e.g., through release of non-CO_2 GHGs).
	Noise	Effect of the mCDR option on the ambient noise level.
	Ecosystem	Effect of the mCDR option on biota.
Cost	CO_2 removal costs	Marginal removal cost (assuming a fully established system).

parameters	Investment intensity	Investment cost to build at least one unit.
	Maintenance cost	Cost for maintenance, including human resources.
	MRV costs	Effort and costs for carbon accounting and evaluation of removal.
Systemic parameters	max. CO_2 removal potential	Maximum removal capacity scaling as permitted by constraints (e.g., area, energy, resource limitations)
	Permanence	Carbon reservoir for storage/sequestration (geological, marine biomass, marine soils/sediments), and the expected length of storage.
	MRV capability	The concept MRV is about “Monitoring, Reporting, and Verification”. Here, we use this term to describe the ability to measure/estimate carbon fluxes/stock changes and to monitor the environmental impacts, and to verify the amount of removed CO_2.

2.2 Data collection, calculations and quality check

Data on mCDR options were assembled by researchers from the German BMBF funded research programs CDRmare and CDRterra, gathered during two workshops (Drübberholz, November 2022; Kiel, June 2023). This expert-driven process brought together participants from various academic disciplines involved in CDR-related research addressing technological, environmental, social, legal, and economic aspects. The participants developed mCDR options based on peer-reviewed literature, reports, resources from their current projects and German-specific information provided by state agencies like the Federal Environment Agency (UBA) and Federal Institute for Geosciences and Natural Resources (BGR). Additionally, literature databases specifically focused on CDR such as the carbon dioxide removal portal (https://carbondioxide-removal.eu/en/news/) were used. Nevertheless, the list of options based on the three main mCDR methods is not meant to be exhaustive.

The data was compiled in a fact sheet for each mCDR option (see SI). Each option detailed an annual removal target of 10 Mt CO_2 and all estimates related to the demand/input and output categories were calculated at this scale. If an option did not reach this scale due to, for example, resource restrictions, a maximum removal estimate (in units of Mt of CO_2 yr^{-1}) was provided and all other estimates related to the demand/input and output categories were calculated accordingly. The cost and technical feasibility were estimated by using the sources described above and supported by our technology consulting partner (fichtner.de). The technology readiness level (TRL) (SI Table S2), assigned to each method is the lowest level depicted in the whole chain of technologies necessary for the respective mCDR implementation. Together with the fact sheet, a schematic drawing of the options was developed (see Figures S3.1.1 -S3.3.1) together with a summary figure (Figure 1). Finally, the experts were asked to provide possible bottlenecks with regard to, for example, resource constraints, and to identify unknowns and research gaps.

3 Collection of marine carbon dioxide removal (mCDR) options

The mCDR collection includes ten options (displayed in 3 classes in Fig. 1) for carbon storage and sequestration in the marine environment. In the following, we will briefly describe the functioning of the option, the estimated technology readiness, the resources that would be required to scale this option up to 10 Mt CO2 yr^{-1} removal rate, the expected costs for such operations, and key uncertainties (for more details, please see the SI). Discussions of the expected environmental effects, and challenges with regard to monitoring, reporting and verification for the options will be in section 4.

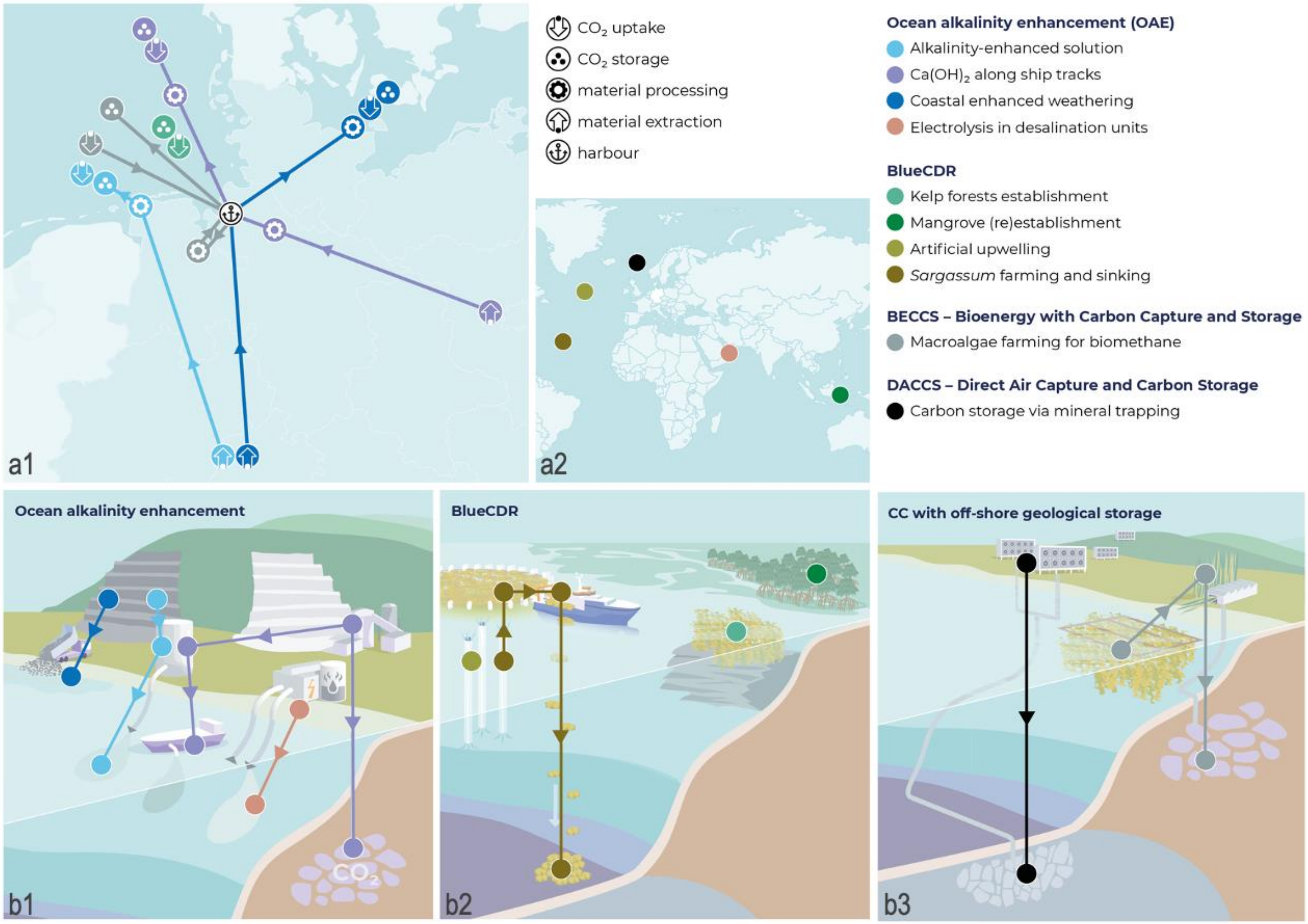

Figure 1: Schematic overview of the ten mCDR options (clustered in three categories).

(a1) Map of Germany indicating the locations chosen for the implementation linked to the region where resources would be available;

(a2) World map for chosen implementation locations for international options (3.1.4, 3.2.2-3.2.4, 3.3.2).

(b1-3) Schematic drawings of the mCDR options showing sources for CO_2 capture linked to CO_2 storage for the different mCDR categories: ocean alkalinity enhancement (OAE, b1), ecosystem-based carbon dioxide removal in the marine environment (blueCDR, b2), and options with marine geological carbon storage (mCS, b3). The colored dots in b1-3 denote processes in the whole chain of operation, e.g., material extraction, material processing, and implementation, while the arrows denote the movement of material down the chain. Note, for option 3.1.3, the deployment area is both in the North Sea and the Baltic Sea

3.1 Ocean Alkalinity Enhancement - mCDR options increasing physical-chemical carbon uptake through the addition of alkalinity

Solutes of weathered silicate and carbonate rocks naturally add alkalinity to the ocean, which increases its CO_2 storage as dissolved inorganic carbon (DIC) (Archer, 2005; Bach et al., 2019). The alkalinity-enhanced seawater at the ocean surface reacts with the CO_2 at the air-sea interface and forms bicarbonate ions, which can be kept in solution for time scales of 100,000 years (Falkowski et al., 2000; Ilyina et al., 2013; Köhler et al., 2013; Köhler, 2020; Renforth & Henderson, 2017). The weathering of alkaline minerals is a negative feedback of the Earth's system regulating atmospheric CO_2 (Archer, 2005; Berner et al., 1983). Ocean Alkalinity Enhancement (OAE) refers to anthropogenic activities with the aim of mimicking the natural process of weathering by adding alkalinity to the ocean to increase its CO_2 uptake (Hartmann et al., 2023; Köhler et al., 2013; Rau et al., 2013) while stabilizing the pH (Hauck et al., 2016; Hinrichs et al., 2023), which has a positive effect on pH-sensitive ecosystems (Albright et al., 2016; Weatherley, 1988).

In the following we describe four OAE options (Figure 1.b1): Option 3.1.1 explores the possibility of enhancing the alkalinity of the German EEZ (North Sea) through electrolysis of seawater in the presence of silicate minerals, option 3.1.2, explores the possibility of ocean liming in the German EEZ (North Sea), option 3.1.3 explores dissolving basalt powder along the German coastline. Finally, option 3.1.4 explores upgrading existing desalination plants to produce alkalinity. Because this option would only be possible on a small scale in Germany, namely on Heligoland (Germany), we decided to explore this concept in an area outside Germany, where freshwater production from desalination plants reaches a scale of 0.6 km^3 yr^{-1} , about the rate related to a CO_2 removal of 10 Mt yr^{-1}, to see its full potential and impacts.

3.1.1 Electrolytic production and addition of alkalinity-enhanced solution from silicate rock on the German North Sea coast

Mined and ground silicate rock from quarries in central-Germany could be transported by carrier/barge to an electrolysis facility on the coast in Northern Germany. The North Sea wind farms would be able to provide off-peak renewable energy that could be used for the electrolysis of the seawater with anodes encased by rock powder (details see Rau et al., 2013). The reaction produces hydrogen, oxygen, silicate and magnesium/other-metal salt (solid), and alkaline enhanced (NaOH) seawater (see SI, Eq. 3.1.1a; Rau et al., 2013). The alkalinity-enhanced seawater could then be released to the North Sea. Since the water with enhanced alkalinity needs to be in contact with the atmosphere for efficient CO_2 uptake, the oceanographic conditions of the German North Sea characterized by high mixing rates (Sündermann & Pohlmann, 2011) would be very amenable to this approach.

While the technology for electrolysis with brine is already commercially used to produce hydrogen, oxygen, chlorine, hydroxide, and acid for various industries (Lakshmanan & Murugesan, 2014), electrolysis with seawater is currently under development (e.g., Ebb Carbon, 2024; Rau et al., 2018), hence we estimate the TRL of this option to be 3 (according to table S2).

To scale this mCDR option to 10 Mt CO_2 yr^{-1}, one would need to dedicate around 30 Mt basalt yr^{-1} (equivalent to 94 % of the current German basalt mining capacity) and around 19 TWh electricity per year (8% of the German renewable electricity production capacity in 2021; House et al., 2007; Rau et al., 2013; calculations see SI 3.1.1). The mining of the rock would use 0.2 Mm^3 of fresh water per year (0.004 % of the total groundwater abstraction in 2019; Gerbens-

Leenes et al., 2018; Wayman et al., 2021) and a minimum of 460 Mm^3 of seawater for electrolysis (Dormann, 2023; 0.001% of the North Sea volume; calculations see SI 3.1.1). At the same time the byproducts, namely hydrogen, chlorine, and oxygen, could be utilized and reduce the energy demand and the cost of the option (Rau et al., 2013).

There is no commercial pilot study available for such an option, hence the cost of such an endeavor is highly uncertain. However, in an optimum case scenario we estimated a cost of 770-1100 Mio. € yr^{-1} for a 10 Mt CO_2 yr^{-1} removal rate including mining, transportation, energy, and investment costs without monitoring (calculations see SI 3.1.1).

One of the remaining challenges regarding electrolysis with seawater is that the constraints on the discharging rate of the alkalinity-enhanced water are unknown. Recent studies recommend values of between 250 - 600 µmol/L to avoid triggering the precipitation of aragonite in coastal regions (Hartmann et al., 2023; Moras et al., 2022). With an assumed 0.86 years of water turnover rate in the North Sea (Sündermann & Pohlmann, 2011), this option would require about 55% of the German EEZ in the North Sea for alkalinity dispersal under a conservative estimation (calculation see SI 3.1.1) and additional in situ modeling study may help to reduce the uncertainty. Also, the role of particles as a trigger for precipitation is not clarified yet (Hartmann et al., 2023; Wurgaft et al., 2021). Another challenge is the erosion of the anode and the formation of precipitates on the electrode surface, which reduces the process efficiency (Jamesh & Harb, 2021). Although in the presence of silicate minerals, the occurrence of chlorine and hydrogen chloride would be suppressed, the question of how to safely dispose or use possible byproducts (e.g., up to 7 Mt of chlorine without applying minerals, similar to 3.1.4) also remains a challenge. Co-emissions from the energy-intensive mining (Moosdorf et al., 2014) could be reduced if the national energy mix is further decarbonised and transportation requirements are reduced if quarries are located close to rivers. Furthermore, a suitable framework for monitoring, reporting and verification (MRV) of alkalinity enhancement is yet to be developed.

3.1.2 Production and spread of $Ca(OH)_2$ along ship tracks in the North Sea

In this option, limestone would be mined in quarries in Germany which are widely spread over the countries adjacent to the North Sea and Baltic Sea. The production of slaked lime ($Ca(OH)_2$) would then be conducted in the lime quarries on-site. The slaked lime would then be transported to a harbour (in northern Germany), where it would be fully mixed with freshwater to produce lime milk. The lime milk is subsequently loaded onto bulk carrier ships and spread into the North Sea along shipping routes. The method could be applied in the German EEZ, and can be extended to the entire North Sea over existing vessel routes.

The production of lime is a mature industrial process with a TRL 9 (Foteinis et al., 2022). The dispersion of alkalinity via ship tracks is less developed. It has been estimated so far mainly based on theoretical discussions with the TRL of 3-4 (Caserini et al., 2022; McLaren, 2012). So currently, we estimate the TRL of this option to be 3.

To reach the 10 Mt CO_2 yr^{-1} removal target, this option would require a minimum of 17.9 Mt limestone (equivalent to 32% of the current German annual limestone production), 15.27 TWh of electricity (~6% of renewable electricity/energy production in 2020), as well as 6.78 Mt of freshwater for the slaked lime production per year. The required land for the mining operation is estimated to be 1858 m^2 while the sea area needed for the alkalinity spreading is 15,500 km^2. Under the assumption that mCDR could have a higher priority for the use of these resources, all the requirements could be fulfilled. During the energy-intensive lime production process (with kiln type that consumes fossil fuels), CO_2 emissions would arise from the calcination process and consumption of fossil fuels (Dowling et al., 2015), which would need to be captured and stored in geological sites (see section 3.3.). Applying less carbon intensive technology (kiln type), and transitioning to renewable energy (Foteinis et al., 2022) would be highly beneficial for this option's efficiency. Low-grade heat is generated during CaO hydration. Currently, its recovery is not practical with the existing lime kilns but might be possible with new lime plants (EuLA, 2014).

The total cost for 10 Mt CO_2 yr^{-1} removal is estimated at 800-1450 Mio € with CCS applied for the lime production (calculation see SI 3.1.2).

One of the remaining challenges is the decarbonisation of the slaked lime production. Even though some processes aiming at zero emission have been proposed (Caserini et al., 2019; Renforth & Henderson, 2017), they still need further evaluation. Another challenge is the assessment of the localized impact produced by slaked lime at the discharge point, due to a temporary increase of pH and alkalinity, of which the environmental side effect is not yet well evaluated and requires additional dedicated experimental studies (Locke et al., 2009; Pedersen & Hansen, 2003). Furthermore, there are presently almost no MRV standards for this practice and a suitable framework thus needs to be built.

3.1.3 Coastal enhanced weathering (CEW) along the German coast

Similar to option 3.1.1, mined and ground alkaline volcanic rock (e.g., basalt) from quarries in central-Germany (Amann et al., 2022) would be transported by carrier/barge to the coast of northern Germany. For this option, the ground rock powder (less than 10 µm grain size) would then be deposited on the coastline in a high-energy environment (we take a 100-meter-wide band, with an average depth less than 10 m along the beach; see SI 3.1.3). The high energy coastal environment could then weather down the grains of alkaline rocks and thus further reduce the energy requirement and cost of the process (Eisaman et al., 2023; Flipkens et al., 2023; Meysman & Montserrat, 2017). The theory would be that the on-site ground rock will dissolve in the coastal seawater, which enhances the alkalinity and the CO_2 uptake of seawater (Flipkens et al., 2023).

The technological feasibility for conducting CEW is high, since this technique has been applied commercially for beach enrichment (TRL 8; "Vesta" 2022), however, the running experiment with the aim for proving the CDR efficiency has not yet offer accessible results, hence by the time of our study, not all of the concept is proven, and we assess that CEW has a TRL of 5.

Germany has coastlines extending over 3,700 km, with approximately 3,300 km shallow and suitable for the coastal enhanced weathering approach (Sterr, 2008), which in an optimal condition can sustain the dissolution of 3 Mt of fine basalt powder annually (calculation see SI 3.1.3). This amount of basalt is roughly 10% of the current German basalt production (BGR, 2021). The total energy consumption for this option is around 614 GWh annually (0.3 % of the German renewable electricity production capacity in 2021), which includes mining and grinding, without transportation. The overall CO_2 removal potential is 1.1 Mt of CO_2 yr^{-1} (calculation see SI 3.3.3), with the possibility of expansion into the continental shelf (e.g., Fuhr et al., 2024; Hylén et al., 2023).

The cost of 1.1 Mt CO_2 yr^{-1} removal is around 160 Mio. € (excluding MRV cost, calculation in SI 3.1.3).

Currently, there are no large-scale implementations of CEW that have achieved the 10 Mt CO_2 yr^{-1} removal target. The verification of the effectiveness as well as the environmental side effects are currently topics of research. The effectiveness would be influenced by the reactivity of minerals (e.g., basalt) under in-situ conditions, the relocation or redistribution of the rock grains (e.g., by wave and tides; Flipkens et al., 2023; Meysman & Montserrat, 2017), or the possibility of spontaneous precipitation of $CaCO_3$ in the basalt minerals pore waters in lower mixing regimes. Concerning verification, remaining challenges are the scale of deployment with the area coverage and the detection of downstream effects due to the continuous dissolution in seawater. The corresponding research questions include: a) What are the basalt dissolution kinetics in German coastal habitats under different biological, chemical, and physical variables, and what are the corresponding carbon sequestration timescales? b) What effects do the release and dispersion of dissolution products have on German coastal ecosystems?

3.1.4 Direct electrosynthesis of NaOH in desalination units in upwelling regions

In many arid regions or on islands, desalination plants are the primary source of freshwater. During the desalination process, seawater is separated into freshwater and a brine. The retained salt in the brine can be split into NaOH and HCl through electrolysis. Retaining the acidic HCl on land and reintroducing the brine along with the alkaline NaOH to the ocean enhances ocean alkalinity. In upwelling areas this approach of OAE would prevent the CO_2-rich upwelled water from emitting CO_2 into the atmosphere (Ali et al., 2021), creating net CDR in the region. While this option could potentially be implemented in a desalination plant on Heligoland, where it would not reach a 10Mt CO_2 removal scale, we decided to explore its potential in upwelling regions (Sea of Oman) where desalination plants produce more than half a gigaton of fresh water annually (DEWE, 2022). This option implementation could be connected to Germany through capacity building and carbon trading (please refer to section 4 for further discussion).

As this approach is currently in the lab-experiment phase with a prototype ("Ebb Carbon," 2024) in development, we assess this option with a TRL of 3.

Utilizing all NaCl from seawater to produce NaOH, achieving 10 Mt CO_2 yr^{-1} removal would require a minimum of 0.47 km^3 of seawater at ~35 g/kg salinity to be processed by a desalination plant yearly (calculation in SI 3.1.4). For example, in 2020, a single large desalination plant in the United Arab Emirates (UAE) produced 0.62 km^3 of freshwater (DEWA, 2022), equating to a processing of 0.6-1.2 km^3 of seawater per year (assuming a recovery rate between 50-90%). Upgrading such existing desalination plants to remove 10 Mt CO_2 would, however, require 42.7 TWh of additional energy per year (SI 3.1.4). This equals ca. eight times the total renewable electricity production in the UAE in 2020 (IEA, 2023). Therefore, the optimistic capacity of this option at this site would be about 1.3 Mt CO_2 yr^{-1}, limited by the currently available renewable energy. Yet, the demand for freshwater production is expected to increase particularly in arid regions (Baggio et al., 2021), which would likely increase the availability of plants for this option. At an efficiency of 70 % of the method, we estimate the extraction of 10 Mt CO_2 to produce around 0.6 km^3 of freshwater..

Making this CDR option energy- and cost-efficient as well as safe faces several challenges. The 8.3 Mt of the by-product hydrochloric acid (HCl) for 10 Mt CO_2 would need safe disposal and storage. In 2022, the global HCl market was estimated to be 15 Mt with an expected growth of 4.2 % by 2032 (ChemAnalyst, 2023). If it was possible to have this CDR option produce H_2 and Cl_2 as byproducts instead of HCl (House et al., 2007; Rau et al., 2018), the by-product Cl_2 gas could be further marketed for various industries (e.g., sewage and wastewater treatment and water cooling systems). The current estimated cost of the electrolysis process (main energy demanding factor) ranges from approximately 900 Mio. € ("Ebb Carbon," 2024; Rau et al.,

2018) to 3850 Mio. € (Rau et al., 2013; Renforth & Henderson, 2017) for a 10 Mt CO_2 removal rate.

It is currently uncertain how OAE in general and this method particularly could affect the environment (see 4.1.3), how MRV could be established (see 4.1.4) and how to safely store the byproduct of HCl if it cannot be sold. It showcases how large scale CDR can alter the market of substantial markets for by products, i.e. HCl, or Cl_2. .

3.2 Blue Carbon Enhancement - mCDR options increasing carbon capture and sequestration by marine ecosystems

Marine ecosystems are habitats of efficient primary producers, such as phytoplankton and seagrass. Primary producers can assimilate CO_2 from the atmosphere through photosynthesis and store it in their biomass, underlying sediments, and/or ultimately release the carbon in form of detritus and/or dissolved recalcitrant carbon sinking to the deep ocean. Kelp forests are estimated to sequester globally about 643 Mt CO_2 yr^{-1} (224-983 Mt CO_2 yr^{-1}), making them a viable marine CDR option (Krause-Jensen & Duarte, 2016). Though the direct CDR capacity might be limited, these options have co-benefits with no/few disbenefits compared to other CDR measures (Gattuso et al., 2018). The permanence of carbon storage in coastal ecosystems is estimated to range from decades to millennia (Duarte et al., 2013; Fourqurean et al., 2012). Organic carbon sunk into the open ocean is estimated to be out of contact with the atmosphere for years to millennia depending on location, storage depth and general ocean circulation and stratification (Siegel et al., 2021). Expanding or managing of such marine ecosystems for enhanced carbon uptake in coastal areas and the open ocean are considered contributions to blue carbon dioxide removal (blueCDR) activities (Mengis et al., 2023).

In the following we describe four blueCDR options (Figure 1.b2): Option 3.2.1 focuses on the reforestation and expansion of kelp forests in Heligoland, as the only site in the German Bight characterized by rocky substrate as prerequisite to kelp forest establishment. This was the only blueCDR option that we were able to explore with the expertise present and at scale within the German jurisdiction. The (re)establishment of seagrass meadows and salt (tidal) marshes as mCDR options within Germany might hold blueCDR potential, especially for non-tropical coastal regions like Germany (Borchers et al., 2022; Macreadie et al., 2021; Stevenson et al., 2023). Nevertheless, since blueCDR options are of large interest and likely a low-regret method (Gattuso et al., 2021), and the potential development of carbon trading schemes under Article 6 of the Paris Agreement could allow for the exploration of CDR outside one's own territory, we decided to explore some of the options outside of Germany to comprehend the scale and efforts associated. For discussions concerning the implications of such activities please see section 4. Option 3.2.2 similarly to option 3.2.1 explores the possibility of (re)planting and expanding of coastal ecosystems, in this case mangroves at the coast of Indonesia. For the last two options we move to recently suggested open ocean blueCDR options (Gouvêa et al., 2020; Wu et al., 2023). Option 3.2.3 explores the use of artificial upwelling (AU) systems to fertilize phytoplankton, enhance productivity and subsequent carbon sequestration through enhanced export. Option 3.2.4 employs the same AU systems to fertilize *Sargassum* farms in the South Atlantic gyre, where the biomass is subsequently harvested and sunk.

The suggested approaches differ from conservation and restoration actions: the first one reduces the loss and thereby avoids GHG emissions of possible degrading marine ecosystems, while the second one restores already degraded marine ecosystems to their baseline state. These two actions avoid CO_2 emissions or restore natural sink capacities and should not be considered as CDRs (Mengis et al. 2023)

3.2.1 Introduction of kelp forests in the coastal waters of Heligoland

The expansion of existing and afforestation of new kelp forests poses an option to sequester CO_2 from the atmosphere. Currently, the only kelp site in the German Bight is Heligoland which could be used as a testing site. For any afforestation measure, young kelp sporophytes need to be produced for seeding. Therefore, local kelp sporophytes (*Laminaria hyperborea*) would be collected when they are fertile and their spores would be released. The spores would be used to produce "green gravel", little stones seeded with young kelp (Fredriksen et al., 2020). After an initial growth period in the lab, the green gravel would be ready to be brought out to the afforestation site, where they could be directly dropped from a boat. Several environmental parameters, such as suitable rocky substrate, light availability, water temperature, and nutrients, are required for the growth of kelp, with temperature being the most important one (Dean & Jacobsen, 1984; Tittley, 1991). While suitable temperature conditions prevail within most parts of the German Bight (Bolton & Lüning, 1982), a necessary rocky substrate for the kelp to attach to is found only around Heligoland. For further expansion, a rocky substrate would be needed to be established at sites with suitable depth ranges.

The green gravel approach is an established method and already in use in other regions (Alsuwaiyan et al., 2022; Fredriksen et al., 2020), therefore, we rate the TRL between 8 and 9. To achieve the target of 10 Mt of CO_2 yr^{-1} removal with this option, an area of about 8 000 km^2, equivalent to about one-tenth of the German Bight's total area, of kelp forest would be needed (calculation see SI 3.2.1). The potential area for the afforestation of kelp in Heligoland is around 13 km^2 (calculation see SI 3.2.1). Most of the coastal area of the German Bight has a muddy substrate, hence the potential within the German Bight is not as big as in other coastal areas. In contrast, most of the shores along the European Atlantic coast have a rocky substrate and would therefore be better suited for kelp afforestation.

To establish 8 000 km^2 of kelp forest, about 3 000 000 t of green gravel would be needed. With an estimated price of 6.28 € per m^2 of newly established or restored kelp forest the costs to afforest 8 000 km^2 would accumulate to a total of about 50 billion € (Fredriksen et al., 2020), with an unknown cost for additional substrate on top. It is important to note that this would be a one-time investment and the subsequent annual costs would be limited to monitoring the annual carbon uptake and the potential need for replanting to maintain the carbon sequestration. The material and energy needs are limited to the time of collection of fertile kelp, the cultivation phase, and the deployment of the green gravel.

Currently, one of the major questions is the long term fate of the carbon captured in the kelp, once the plant detaches. For a long-term storage of CO_2, it would need to drift to the open ocean and sink deep enough to be sequestered in the sediment (Filbee-Dexter, 2020; Krause-Jensen & Duarte, 2016). However, if the kelp gets washed ashore, it would decompose and the CO_2 would be released back into the atmosphere. The washed-up kelp could potentially be used as a co-product like fertilizer or for the production of bioenergy, but only durable sequestration or storage of the carbon would qualify as CDR (Smith et al., 2023). To further scale up this option within the German Bight, the challenge will be the establishment of a rocky substrate in the large coastal areas. However, this option could be applied on many rocky shores in other locations.

3.2.2 Mangrove (re)establishment in Indonesia

Mangrove forests store a considerable amount of carbon in their biomass and sediments (Alongi, 2014), sequestering ca. 15-73 Gt CO_2 yr^{-1} globally (Donato et al., 2011). They grow in tropical to subtropical areas, making them currently unsuitable for the German coast. It is estimated that 20 to 35% of the world's mangrove forests have been lost over the last 50 years, mostly due to anthropogenic activities and extreme climate events (Polidoro et al., 2010). In this option, the potential of reforestation and expansion of mangroves forests on the example of Indonesia is explored, since it currently hosts over 20% of the area of the world's mangroves population (Giri et al., 2011). Over the last 30 years, Indonesia has lost about 8,000 km^2 of mangroves, and estimates of the initial area of mangrove forests in Indonesia range between 42,000 km^2 and 77,000 km^2 about 35 years ago (Ilman et al., 2016), while the current area is about 31,900 km^2 (Alongi et al., 2016). Therefore, Indonesia has great potential for mangrove (re)establishment and consequently, carbon dioxide capture and storage.

Planting mangroves is a process that is well studied and established, we estimate the TRL to be 9. Before replanting, certain abiotic parameters such as physico-chemical characteristics (salinity, pH), hydrodynamics (waves energy, inundation time) and topography (slope) would have to be checked to select species for planting in suitable zones and improved survivability of the seedlings. Propagules or seeds can be gathered and planted directly, or nurseries can be set up. While nurseries would require a larger time and cost investment, they increase the survivability of the seedlings (Hsiung et al., 2024). If necessary, hydrologic conditions might need to be restored to address stressors that have previously caused their declining numbers, by e.g. setting up breakwaters, or digging channels. In this case, more time and resources would be needed.

While replanting mangroves describes a simple enough approach, scaling the operation to achieve the 10 Mt CO_2 uptake remains a challenge, since it would require the availability of an area of ~9,400 km^2 (see SI 3.2.2). However, Sasmito et al. (2023) showed that only about 1,900 km^2 are currently suitable for mangrove (re)establishment, which would lead to an uptake of 2 Mt CO_2. Planting mangroves on an area of 9,400 km^2 would require an investment of 3.4 billion € (Cameron et al., 2019), which includes 1 billion seeds, planting, facilities and infrastructure, and maintenance per km^2 for a 10 Mt CO_2 yr^{-1} removal scale.

Remaining uncertainties concerning this approach include the exploration of sufficient areas if there would be an intent to scale up this approach, including the corresponding investment costs. Monitoring, reporting and verification of the carbon sequestration, which is currently mainly driven by the efforts of volunteers, would have to be scaled up and operationalized, for which organizational structures would need to be established.

3.2.3 Artificial upwelling to enhance plankton production in the North Atlantic

Artificial upwelling (AU) is based on the idea to introduce pipes in open ocean oligotrophic waters to pump up nutrient-rich deeper water to the surface ocean and thereby enhance primary production and export production with the aim to generate an additional CO_2 flux from the atmosphere into the surface ocean.

If this idea (for which we currently estimate a TRL of 2) would be further developed, one possible application of the option could be the North Atlantic ocean, where long wave-energy powered pipes of 1000 m length would be installed (see SI 3.2.3 for more info). The necessary infrastructure for this option would include facilities to produce durable pipes made out of steel, plastic or other new materials, ships to install and maintain the pipes in the North Atlantic and a large network of remote sensing technologies (e.g., satellite images and ARGO floats) for MRV purposes (e.g., Mengis et al., 2023). The pipe-covered area needed in the North Atlantic to hypothetically reach 10 Mt CO_2 yr^{-1} removal via 1000 m long pipes may be calculated from down-scaled global modelling experiments and would reach a size of 682,000 - 1,706,000 km^2 (2-5 times the size of Germany; Jürchott et al., 2023).

This would translate into 40,000 individual pipes and an investment of ca 2.2 billion € (based on the assessment that one individual 500 m pipe would cost approximately $ 60.000 and would be able to remove 250 t of CO_2 yr^{-1}, see SI 3.2.3 for more information). Although shorter pipes are expected to cost less money compared to longer pipes, longer pipes in model experiments have been found to be more effective in removing CO_2 from the atmosphere (Oschlies et al., 2010a; Yool et al., 2009). The calculated pipe covered area as well as the costs to reach 10 Mt CO_2 yr^{-1} removal in the North Atlantic are highly uncertain (also given the low TRL), but some expected side-effects and the duration time (see discussion below) of the additionally added CO_2 can already be assessed based on modeling studies. The option is expected to require a total energy demand of 1.4 TWh yr^{-1} including the pipes production and ship operation (see SI 3.2.3 for more details).

One concern to this AU option, is the fact that the approach would also transport heat and salinity and thereby change the ocean stratification and, eventually, the ocean circulation with potentially substantial impacts on climate (Kwiatkowski et al., 2015). As long as AU is continuously applied, the duration time of additionally stored CO_2 in the ocean is expected to range from decades to millennia (Siegel et al., 2021). It is, however, worth noting that AU, once deployed, would need to be deployed continuously to further increase and keep the additionally added CO_2 stored in the ocean (Keller et al., 2014; Oschlies et al., 2010a). If AU is abruptly discontinued, the surface ocean would immediately respond with CO_2 outgassing, while at the same time additionally stored heat in the ocean interior would radiate back to the atmosphere and within years to decades atmospheric temperatures would rise even above the reference simulation (Oschlies et al., 2010a). Another considerable uncertainty within the development of this option is the durability and stability of the pipes once deployed.

3.2.4 Sargassum farming and sinking in the South Atlantic gyres

For this CDR option, holopelagic Sargassum (*Sargassum fluitans* and *S. natans*) would be grown off-shore in free-floating aquafarms placed in the South Atlantic subtropical gyre. Nutrients for growth would be provided through artificial upwelling of nutrient-rich deep water from 400 m depth, using upwelling pipes based on the Stommel principle for a perpetual salt fountain (Stommel et al., 1956). This type of artificial upwelling would not require external energy as the nutrient-rich deep cold water would warm as it comes up and parallelly downwelling warm water from the surface. Environmental conditions (temperature, light, salinity) in this region are favorable for growth of pelagic Sargassum (Gouvêa et al., 2020) and make the implementation of the Stommel upwelling pipe system possible (Kemper et al., 2023).

We estimate the TRL of this option as 2, with the main bottleneck being the cost of the development of the prototype pipes (see section 3.2.3).

To sequester 10 Mt of CO_2 yr^{-1}, 57.5 Mt of Sargassum biomass would need to be sunk to the deep sea every year and the total energy demand is 1.7 TWh yr^{-1} (calculation see SI 3.2.4). Sargassum increases its biomass by fragmentation at a rate of 5-10% per day, which means to grow and harvest 0.16 Mt of biomass on a daily basis, a Sargassum standing stock of 4.63 Mt biomass would need to be maintained. To sustain growth, 8,578 m^3 of deep ocean water from 400 m depth would need to be upwelled per second (~half of the water discharge of the Mississippi river). This farm would take up an area of 1,324 km^2. The harvested biomass would be mechanically shredded to extract the nutrients and would be able to be fed back to the aquafarms, reducing the above-mentioned amount of deep water needed for fertilization ("Sarga Agriscience," 2021). The shredded biomass will then be pressed into bales and released back to the ocean, where they would sink down, since gas vesicles of the Sargassum would be destroyed in the shredding process, which causes the biomass to lose its natural buoyancy (Baker et al., 2018; Johnson & Richardson, 1977). The logistical effort could be reduced by automated on-platform workflows for farming, harvesting and sinking at the same place.

Due to the low TRL, cost estimations for this option are highly uncertain. Costs of investment and maintenance of infrastructure, including workforce and transportation, would amount to around 1,060 € per tonne of CO_2 removed, if scaled-up linearly this would come up to 10.6 billion € for the 10 Mt CO_2 yr^{-1} removal.

Many uncertainties arise with this option, mainly due to the need to establish the infrastructure, as well as the monitoring. Consequences of impacts on ocean physics and circulation via changes in stratification, as well as from the Sargassum farms and the sunken biomass (e.g. on oxygen levels) are not well understood and need to be addressed in future studies.

3.3 Off-shore Geological Carbon Storage (mCS) - mCDR options with technological carbon capture and subsequent storage in geological formations

Carbon storage in geological formations represents a necessary contribution if technological carbon capture approaches want to achieve carbon removal, like bioenergy carbon capture (BECC) and direct air carbon capture (DACC). In the following, we consider maritime or off-shore storage of CO_2 (mCS) in combination with BECC or DACC. Note that geological storage of carbon emissions from fossil processes (often referred to as fossilCCS) is distinct from these mCDR approaches, since in this case fossil emissions are avoided, rather than atmospheric carbon being removed; fossilCCS does not constitute a CDR method (Smith et al., 2023). The concept of geological CO_2 storage is based on controlled injection of dissolved or liquified CO_2 into porous rocks in the subsurface, so in a geological reservoir. Depending upon the properties/type of the target host rock, the CO_2 can be trapped by several mechanisms, which comprise trapping by an impermeable cap rock or sediment cover (structural trapping), capillary forces in pores (residual trapping), dissolution in water (solubility trapping), and mineral carbonation reactions (mineral trapping).

Two options for geological storage are of particular interest and explored here in more detail (Figure 1.b3): Option 3.3.1 looks into the possibility of marine biomass for bioenergy generation combined with structural trapping of CO_2 in sandstone formations/saline aquifers that exist in the German North Sea. Deep saline aquifers have a high CO_2 storage capacity due to their regionally large extent, but are still mostly unexplored (Bachu, 2015). Estimates for CO_2 storage in the German EEZ suggest total storage capacities of 4-24 Gt CO_2 (Knopf & May, 2017). Time scales of geological CO_2 storage in sandstone formations, while dependent on the regional conditions, can mostly be considered long-term, if not permanent, with a projected minimum of 98% of the stored CO_2 remaining in the reservoir for 10,000 years (Alcalde et al., 2018). Another option (3.3.2), albeit outside of Germany, explores the possibility of direct air carbon capture combined with mineral trapping of CO_2 through injection of CO_2 into porous basaltic rocks. The basalts form the upper part of the oceanic crust, which is why the majority of them are located offshore in the deep sea and outside the German EEZ. Mineral trapping in basalts is an interesting option for CO_2 storage, as carbonate mineralization occurs rapidly compared to the more conventional CO_2-storage in sandstone formations, which on the one hand minimizes the risk of CO_2-leakage, and on the other hand provides long-term storage by immobilizing the CO_2 (Kelemen et al., 2019). Due to the chemical composition of basalts, which is rich in calcium, magnesium, and iron, the injected CO_2 can react with these elements to form carbonate minerals in the pore space of the rock. Furthermore, impermeable sediments that cover most of the oceanic crust are assumed to impede CO_2-leakage from the reservoir and, thus, contribute to safe storage conditions. According to the calculations of Snæbjörnsdóttir & Gislason (2016), fractured and porous basaltic flanks of mid-ocean ridges bear a storage capacity of $>10^5$ Gt CO_2, exceeding the expected CDR needs manifold. This option would take CO_2 captured in Germany and store it in Norwegian waters, which would require refined agreements concerning CO_2-trade between Germany and Norway, as discussed in section 4.

3.3.1 Biomass from macroalgae farming for biomethane production combined with carbon storage in saline aquifers in the North Sea

For a marine feedstock for bioenergy combined with carbon capture and storage, macroalgae could be cultivated and harvested. Plantlets would be set into nearshore floating macroalgae farms (Buck & Buchholz, 2004), which would then be transported offshore and moored within the German exclusive economic zone (EEZ) (Buck et al., 2018). The macroalgae would be harvested once a year, and transported to biogas upgrading plants ideally located in northwestern Germany. The bioenergy plants would need to be retrofitted with carbon capture units, from which the CO_2 is then collected and transported to saline aquifers in the North Sea (with a capacity between 4-24 Gt CO_2, Knopf & May, 2017).

At present, given the highly commercialized coastal seaweed cultivation in Asia, and its absence in North Europe, we estimate the TRL of this option to be 6 (see SI for estimation).

For this option, to reach 10 Mt CO_2 yr^{-1} removal, assuming an average annual productivity of 20 kg fresh mass per square meter (FM)/m² (Buck & Buchholz, 2004; Chen et al., 2015; Chung et al., 2013; Fernand et al., 2017; Kim et al., 2017; Roesijadi et al., 2010), one would need a total area of 2,358 km² (approximately 8.3 % of the total area of the German EEZ) for macroalgae cultivation to produce a total of 115 million tonnes macroalgae FM per year (see SI 3.3.1 for calculations). A benefit is the production of biomethane as an energy carrier: Although energy is required for harvesting, bioenergy plant operation, and CCS, the model plant produces 4.8 Mio. m^3 biomethane, as well as additional heat for external use.

Not considering potential revenues from selling the products, the CO_2 removal cost is estimated at 83 €/ton CO_2, which would amount to 830 Mio. € for the 10 Mt CO_2 yr^{-1} removal scale. If this option was scaled up to this order of magnitude, the construction of new, large-scale (MW-size) plants close to the shore would be reasonable, instead of relying on a big number of decentralized, small-scale plants. While this would impact investment costs, it would reduce the efforts of biomass and CO_2 transportation.

One challenge associated with open ocean macroalgae cultivation is the durability and maintenance of the floating farms, which are susceptible to damage under severe weather conditions in the North Sea (Buck & Buchholz, 2004). One uncertainty of this mCDR option concerns the productivity of macroalgae in the German EEZ, as the estimation given here is highly idealized. Macroalgae growth depends on water temperature, nutrient availability, light and ambient ocean currents. These conditions exhibit significant seasonal variations and are also affected by climate change (Buck & Buchholz, 2004; Grabemann & Weisse, 2008). Previous studies have illustrated that cultivated macroalgae in the North Sea showcase resilience to the high energy environment, even amid severe storm conditions. This implies a potential for macroalgal cultivation within such challenging maritime settings (Bartsch et al., 2008; Buck & Buchholz, 2005; Fortes & Lüning, 1980). Finally, the use of more than 10% of the German EEZ area for the macroalgae production is surely challenging, given the strong competition for area usage within the EEZ. Another challenge for the CDR option is the anaerobic digestion process in biogas plants for macroalgae feedstocks due to unwanted impurities, e.g., polyphenols, sulfur, sodium chloride, and heavy metals (Murphy et al., 2015). However, several pre-treatment methods have been suggested in the literature to enhance biomethane yields (Chen et al., 2015; Chung et al., 2013; Suutari et al., 2015).

3.3.2 Off-shore carbon storage via mineral trapping in North East Atlantic basalts combined with direct air carbon capture

For this CDR option we explore the possibility of CO_2 being captured in Germany by DACC facilities fed with energy generated by offshore wind parks in the North Sea. The captured CO_2 could be transported via cargo ships to an offshore injection site. In the North East Atlantic a basalt volume of approximately 90,000 km^3 has been identified, of which 30,000 km^3 are in Norway at subsurface depths between 1.500-3.000m (Planke et al., 2021). For this CDR option, we assume this platform to be located at the Vøring plateau at the North Western Norwegian margin, since the basalts of this region are well studied (Planke et al., 2022) and may have a storage potential of several Gigatons of CO_2 (under investigation; Planke et al., 2021; Rosenqvist et al., 2023).

Capturing CO_2 from the atmosphere by using DACC facilities is at the demonstration stage at TRL 6 (IEA, 2022). The concept of offshore CO_2 mineralization still needs to be prototyped and applied in the future. Therefore, the TRL for offshore CO_2 storage in basalts is estimated to be 3-4.

If this option was to be scaled to capture and remove 10 Mt CO_2 yr^{-1}, the DACC would need 18 TWh of energy generated by renewable energy sources (Borchers et al., 2022; Heß et al., 2020), that is ~85% of the energy currently transferred to shore by the North Sea wind parks (Tennet, 2023). The area and the amount of material required to build DACC facilities to capture this quantity of CO_2 are highly uncertain and subject to debate (Chatterjee & Huang, 2020; Realmonte et al., 2019, 2020). For CO_2 transport, the captured CO_2 has to be liquefied (~1.51 TWh/10Mt CO_2, see SI 3.3.2) and stored in intermediate tanks. Assuming a distance of 1,800 km, three injection wells, and discharge rates between 1,375 - 2,750 m^3 h^{-1}, transporting 10Mt CO_2 yr^{-1} requires ~40-140 trips with at least three large, four medium, or eight small cargo ships, respectively. On site, floating production and offloading units (FPSO) with risers for each well are needed for continuous CO_2 injection. Regarding the injection of CO_2, two different approaches exist: either CO_2 can be injected as a “pure” phase or it can be mixed with seawater (see SI 3.3.2). In case of “pure” CO_2 injection, the CO_2 can be heated and compressed by seawater or waste heat recovery on board (to 10°C, 60 bar). Then, compression for injection to, e.g., 300 bar, requires 0.094 TWh/10Mt CO_2 (see SI 3.3.2)).

Among others, the costs of capturing CO_2 depend on the DACC technology and the energy costs, which makes the calculation of future capture costs challenging (IEA, 2022). The same applies for the storage technologies, due to low TRLs future cost estimates are not feasible.

In Iceland, ongoing small-scale projects combine DACC (capturing on the $ktCO_2\ yr^{-1}$ scale) and basalt CO_2 storage onshore ("Mammoth," 2022; "Orca," 2021). While in this option DACC is used for the feed of CO_2, it is also possible to use bioenergy (similar to 3.3.1). Since storing CO_2 via mineral trapping in offshore basalt formations is still below the prototype stage, many research questions remain: Is the injection of supercritical CO_2 or CO_2 dissolved in water the more suitable option for the Norwegian Sea? Is there an active aquifer in the basaltic layers with flow fostering CO_2 distribution? How does clathrate formation affect the injection scenario? How fast do the carbonates precipitate, how does the reaction affect the pore space geometry and hydraulic properties of the host rock? In which sub-bottom depth is the CO_2 injection safest and most efficient? Getting a profound knowledge of these fundamental questions facilitates finding the best location to drill and estimate the amount of drill holes required to trap a certain amount of CO_2, which in turn affects the costs to realize this mCDR option.

4 Discussion

The collection of mCDR options in this study covers different approaches to carbon storage and sequestration in the marine environment. We explore four options for ocean alkalinity enhancement (OAE), four options for enhancing the uptake of blue carbon ecosystems (blueCDR), two of which use artificial upwelling systems (AU), and two options involving geological off-shore storage (mCS).

Within the generated mCDR option collection, six out of ten options could potentially reach the scale of 10 Mt $CO_2\ yr^{-1}$ removal, of these six, four would have the CO_2 captured within German borders, and three options are located entirely within German jurisdiction (see Figure 1). The blueCDR options based on introducing kelp on Heligoland (3.2.1), and mangrove replanting in Indonesia (3.2.2), as well as the OAE options through electrolysis in desalination plants (3.1.2) and coastal enhanced weathering (3.1.3) did not reach 10 Mt $CO_2\ yr^{-1}$ removal under the assumptions made here.

From a global viewpoint, the assessment of marine-based CDRs by Gattuso et al. (2021) saw alkalinity enhancement as the front runner when it comes to CDR potentials, but our site-specific assessment highlights that different implementations of the same method can result in differences in the regional capacity. Taking the options for OAE as an example, adding an alkalinity-enhanced solution in the North Sea (3.1.1) and liming along ship tracks (3.1.2) could potentially reach the scale of 10 Mt $CO_2\ yr^{-1}$ removal, while neither coastal enhanced weathering (3.1.3) on the same site nor electrosynthesis in desalination units (3.1.4) on a more suitable site could do it. Similarly, while Gattuso et al. (2021) consider blueCDRs to have very low direct CDR potential globally, our assessment shows that while it is possibly true for kelp forest establishment (3.2.1), other blueCDR options, like mangrove (re)establishment (3.2.2) can reach the megaton scale, and both artificial upwelling (3.2.3) and sargassum farming and sinking (3.2.4) can potentially rise to the challenge.

The techno-environmental comparison of these approaches is challenging, since the options are distinct in both their capture mechanisms - ranging from ecosystem sink capacity enhancement, to enhanced chemical weathering, to technological direct air or point source carbon capture - and their storage processes - ranging from marine biomass, to dissolved inorganic carbon in the water column, marine sediments or varying geological formations. As a result, the mCDR options require different types and amounts of resource inputs, rely on different technologies and infrastructure, and have different co-benefits and side-effects. By scaling the CDR options to the same annual removal rate (10 Mt CO_2 yr^{-1}), we attempt to allow for some comparability with respect to factors like area or energy demand, environmental effects and MRV challenges and possibilities, which we will explore in the following.

4.1 Comparison of marine CDR options - TRL, energy and area demand, and bottlenecks

The technology readiness level (TRL) assigned to the mCDR options gives an estimate of the current availability of the technological components of the options, and therefore the development time before possible implementation. The generated collection encompasses mCDR options at all TRLs, with low TRL for both AU options (3.2.3, 3.2.4), and reasonably high TRL for the two blueCDR options managing ecosystems (3.2.1, 3.2.2). While high TRL options are in a rather mature state, having most technological components proven and tested in past and ongoing pilot projects (e.g., IEA, 2022; Raw et al., 2023), low TRL options are still in the concepts' development phase and only some theoretical estimations exist in the literature. For those low TRL options, many of the parameters in this study hence are first estimates and therefore rely on reasonable assumptions when scaled up to a 10 Mt CO_2 yr^{-1}, which is a clear limitation to our study, and should be considered when interpreting our findings.

Low TRLs certainly can be considered bottlenecks for the mCDR options (e.g, 3.1.1, 3.1.2, 3.1.4, 3.2.3, 3.2.4, 3.3.2). It is noteworthy that only the ecosystem-based options have TRLs higher than 6 (Figure 2). Other bottlenecks are more method-specific (Table 2). For the high energy demand OAE options (3.1.1, 3.1.2, 3.1.4) as well as for the DACCS option (3.3.2), the main limiting factor would be the supply of renewable energy to decarbonize the process chain, whereas the BECCS option (3.3.1) shows a net energy provision in the form of biomethane and heat. For rock based OAE options, the considerable demand for material would also pose a challenge.

In contrast, the blueCDR options would have low energy demands, since the energy demand in nurseries or upwelling pipes is relatively small, but would require considerable marine space for their implementation. This limitation prevented both ecosystem-based options (3.2.1, 3.2.2) to reach the 10 Mt CO_2 yr^{-1} removal scale. If marine biomass for BECCS or Sargassum farming are to be employed to relieve pressures on land, the engineering for suitable open ocean farms for seaweed in the North Sea remains a challenge. The area and energy demands of harvesting and transporting 115 Mt of macroalgae biomass could potentially present another bottleneck in an at-scale implementation. In addition, technological innovation in the open ocean engineering, deployment and maintenance of the farm structures and upwelling pumps would be necessary before these options can be implemented. Similarly, spreading alkaline solutions in the ocean requires access to large areas (3.1.1, 3.1.2, 3.1.4).

In contrast, area demand of the DACCS option is less than 100 km^2 (3.3.2), with the highest demand arising from the DACC plants. While the area demand is often assumed to be less problematic for mCDR options compared to land-based CDR options, challenges with respect to accessibility of large ocean areas (3.1.1, 3.1.2, 3.1.4, 3.2.3) and potential conflicts with other uses (e.g., conservation, offshore wind, etc.) in more coastal areas (3.1.3, 3.2.1, 3.2.2, 3.3.1) remain.

For the BECCS and DACCS options (3.3.1, 3.3.2), the lack of existing infrastructure (carbon capture facilities, transport infrastructure and offshore platforms) for the geological carbon storage as well as the high energy demand for the carbon capturing process limit their potential.

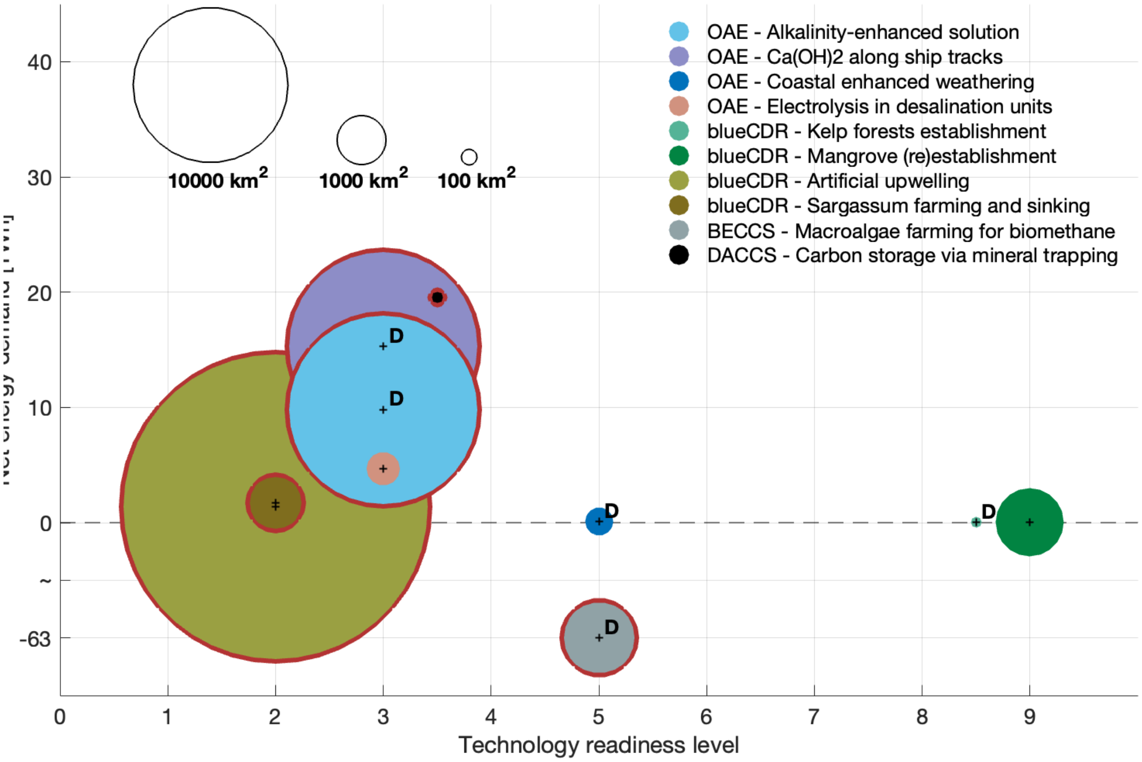

Figure 2: Summary and comparison of mCDR options with respect to technology readiness level (TRL), net energy demand and area demand as described in section 3. Note that the area usage displayed here includes estimated land and sea surface area, where the sizes of the area are in logarithmic scale. Net energy demand is given as demand minus supply, which can lead to negative values. Red circles around the options indicate that they do reach the 10 Mt CO_2 yr^{-1} removal. For the options that do not reach the 10Mt CO_2 yr^{-1}, their net energy and area demand are based on their maximum potential. "**D**" on the upper right side of the option indicates options situated within Germany.

4.2 Comparison of marine CDR options - Environmental effects

The mCDR options aim to alter biological, chemical or geological processes with the goal to increase carbon uptake, yet alongside this desired effect likely come a variety of unintended environmental effects of varying predictability. The extent of the possible environmental effects at a specific scale at a specific site is difficult to quantify without dedicated studies (e.g., model studies with site-specific boundary conditions) and will have to be subject to further investigation. We gathered possible expected environmental effects from literature and compiled them here.

The possible impacts of OAE on the wider marine ecosystem on short to long time scales require more research (Albright et al., 2016; Bach et al., 2019; Cripps et al., 2013; Ferderer et al., 2022; Gately et al., 2023; NAS, 2021). The introduction of alkaline substances into seawater could allow for additional CO_2 uptake while stabilizing the pH, although this does not reverse previous acidification (Hinrichs et al., 2023; Hutchins et al., 2023). The addition of alkalinity is reported to have a positive effect on ecosystems that are sensitive to ocean acidification (Albright et al., 2016; Weatherley, 1988), however, it is also shown that less dissolved CO_2 may reduce growth rates of calcifying organisms (Langer et al., 2006). At the point of alkalinity injection, OAE might cause localized temporary pH and alkalinity spikes, which might be ecotoxic and detrimental for the affected ecosystems (Locke et al., 2009). On a longer time scale, such an intervention could impact the physiology of marine organisms and the ecosystem structure (Roberts et al., 2010). If OAE options would introduce minerals or their solution into the ecosystem (3.1.1, 3.1.3), this would likely have a fertilization effect (Hauck et al., 2016; Köhler et al., 2013). OAE therefore could increase the primary productivity on site, but decrease oxygen level and increase acidification in the water column downstream (Oschlies et al., 2010b). Depending on the geochemical composition of the used rock, heavy metals could also get into the water through mineral dissolution or electrolysis and desalination processes (Arribére et al., 2003; Lattemann & Höpner, 2008), which needs to be regulated. The discharge from desalination plants (3.1.4) might be contaminated with filter-cleaning products (anti-scalants and antifoulants) which would impose potential danger to the local environment (e.g., Ahmed & Anwar, 2012; Al-Anzi et al., 2021; Jones et al., 2019). Furthermore, indirect effects from OAE options due to mining activities (3.1.1, 3.1.2, 3.1.3) would likely negatively impact soil, air, and water quality on land, and introduce noise pollution to the environment on and off site (Sengupta, 2021). Also, there are concerns about health risks associated with finely crushed (1-10 µm) material containing fibrous serpentine minerals like asbestos, as well as potential problems with wind-borne transport of fine ground olivine (Hangx & Spiers, 2009).

Environmental effects from blueCDR options could include changes in species compositions, light availability for organisms living on the seafloor or ambient nutrient levels. Furthermore, if biomass is mobilized, its decomposition would cause a decrease of oxygen levels in the adjacent deeper water or on the seabed. However, the introduction of kelp or mangrove forests would provide several co-benefits such as coastal protection, provision of services like food, timber or medicine, provision of habitat for (commercially important) fish species, water purification (Castro et al., 2022; Kayalvizhi & Kathiresan, 2019; Theuerkauff et al., 2020), as well as cultural services, including tourism, religion, and contributing to general well-being (Bandaranayake, 1998; Cuba et al., 2022; Eger et al., 2023).

The environmental effect of AU options is highly uncertain and has so far mostly been assessed within modeling studies. Ocean fertilization from AU options, introducing nutrient-rich deep water to the surface, may shorten food web structure and has negative implications on primary producers via a reduced nutrient content (Baumann et al., 2021; Ortiz et al., 2022). An increase of primary production could lower oxygen provision to deeper waters and increase GHG release (e.g., methane and nitrous oxide; Williamson et al., 2012). Additionally, the artificial upwelling of water may vertically transport microbes, likely impacting the microbiological environment. Changes in temperature, salinity, stratification, and circulation induced by AUs require meticulous study due to their irreversible nature (Oschlies et al., 2010a).

Environmental effects from large-scale macroalgae or sargassum farms are still understudied, but likely include increased or changed biodiversity both at the surface and in the deep sea (Baker et al., 2018; Casazza & Ross, 2008), increased albedo (Bach et al., 2021), reduced light at the surface and possibly co-emission of halocarbons (Keng et al., 2013; Mithoo-Singh et al., 2017). While growing, Sargassum excretes large amounts of dissolved organic matter (DOM) (Powers et al., 2019). Some of the excreted compounds are likely to persist in the ocean as recalcitrant DOM, which would contribute to CDR due to its persistence against microbial degradation

(Buck-Wiese et al., 2023). It has also been shown that existing off-shore Sargassum ecosystems can also contribute to increasing biodiversity and providing a habitat for several species such as turtles, dolphins, and several fish species (Martin et al., 2021). A careful evaluation of open ocean macroalgae farms considering impacts and potential co-benefits on marine ecology, biogeochemistry and fishery is required (Chung et al., 2013; Fernand et al., 2017; Gao et al., 2021; Wu et al., 2023). This includes accounting for offsets from the remineralization of particulate organic carbon (POC) export, the generation of halocarbons, calcification by encrusting marine life, and changes in surface albedo (Bach et al., 2021; Chen et al., 2020; Jia et al., 2022; Krause-Jensen & Duarte, 2016; Pedersen et al., 2021; Wada et al., 2015; Wang et al., 2023). Potential oxygen depletion through biomass remineralization and potential methane and hydrogen sulfide production in the deep sea have been proposed (Levin et al., 2023), but are subject for further studies.

The expected environmental impacts of off-shore geological carbon storage are mainly noise (e.g., Marappan et al., 2022) and CO_2 leakage events. Noise is generated by drilling and pumping or may be produced if active seismic methods are used to explore and monitor the storage site. Passive seismic methods have the potential to reduce noise stressors (Goertz-Allmann et al., 2014). Leakage in the case of dissolved CO_2 injection, is prevented by the higher density of CO_2-charged seawater compared to normal seawater. A higher leakage risk arises if CO_2 is injected as pure phase. Results of a controlled CO_2 release experiment near the Sleipner CO_2 storage site showed that, in case of leakage, CO_2 gas bubbles are dissolved within 2 m above the seafloor and the excess dissolved CO_2 is further dispersed by tidal currents (Vielstädte et al., 2019). Their model indicates that pH changes exceeding seasonal changes are only found within a distance of approx. 80 m from the well. Still, particularly for prolonged leakage and higher CO_2 release rates, increased CO_2 concentrations and low pH bottom waters could have noxious effects on benthic organisms in the vicinity of a leaky well (Vielstädte et al., 2019). The risk of CO_2 leakage is reduced if fast crystallization processes are triggered by the injection.

It is noteworthy that in contrast to land-based CDR options, the environmental impacts of mCDR options are even less constrained by the deployment site due to the continuous ocean medium (Mengis et al., 2023). The blueCDR (including AU) and OAE options, in particular, might not only affect the region of the operation, but could also cause changes downstream as the water masses move (e.g., Berger et al., 2023; Wu et al., 2023), causing among others challenges for the long-term monitoring and verification of carbon storage (Mengis et al., 2023).

4.3 Comparison of marine CDR options - Evaluation and monitoring of mCDR

Comprehensive evaluation and monitoring would be needed to accurately assess the effectiveness and side-effects of the mCDR options. Presently, no standard monitoring protocol for mCDR options is in place.

However, for OAE a best practice guide on responsible research including MRV has been published (Ho et al., 2023; Oschlies et al., 2023). MRV for OAE options would need to consider in-situ pre-conditions. At the release site, mooring stations equipped with autonomous systems to monitor the carbonate system and biological components could provide initial alkalinity signals. Existing observational networks like the Ship-of-Opportunity, FerryBox-integrated, membrane-based sensor measurements in the surface North Sea, with the measuring instruments equipped on repeating commercial vessel, could provide a cost-effective way to observe the surface ocean at a relatively large temporal resolution and spatial coverage (Macovei et al., 2021b). However, in the 10 Mt CO_2 removal scale, if the added alkalinity would spread in the North Sea evenly, it would be difficult to verify the effect on total alkalinity, since the expected change (4.3 µmol/L) is much smaller than the natural seasonal variation of alkalinity on site, (Hoppema, 1990), smaller than the alkalinity sensor accuracy (Sonnichsen et al., 2023) and on par with the current laboratory alkalinity measuring techniques (Bockmon & Dickson, 2015). This means that one would depend on models alongside the observational effort near the discharging site (Ho et al., 2023). Accompanying the evaluation of the mCDR effect, environmental monitoring (e.g., water quality monitoring and fishery management) needs to be in place, due to the various side effects of OAE (see section 4.1.2).

Challenges and ways forward concerning the evaluation and monitoring of blueCDR approaches have recently been outlined (Mengis et al., 2023). To evaluate for example the CDR potential of Sargassum aquafarming coupled with AU, the flow of CO_2 from the atmosphere to the Sargassum biomass needs to be demonstrated using surface ocean pCO_2 sensors and flux calculations based on gas-exchange parameterizations, as well as the permanence and stability of the biomass in the deep sea. After establishing key concepts, surface, submerged biomass stocks, biodiversity, bycatch and environmental parameters (nutrients, trace elements, pCO_2, O_2, DOM fractions) need to be monitored regularly to spot possible impacts and environmental changes. Environmental parameters can be collected to implement the data in a predictive model. Any MRV for AU would be highly challenging, since the additionally stored CO_2 in the interior ocean will move with the currents and get diluted (Mengis et al., 2023).

Finally, in terms of monitoring geological storage sites of mCDR options, many of the developments in petroleum reservoir monitoring could be adapted. The now widespread use of time-lapse seismic reservoir monitoring (Lumley, 2001), as demonstrated at the Sleipner project (Arts et al., 2004), time-lapse (4D) seismic monitoring, gravity field monitoring, surface gas monitoring, and distributed fiber-optic sensing are just some possibilities. Furthermore, the monitoring of storage sites can profit from existing regional geophysical monitoring, local deployment of landers that are equipped with sensors, e.g. DIC sensors, or isotope measurements of cores from monitoring wells to confirm the carbonization reaction.

Table 2. Overview of bottlenecks and research gaps/uncertainty identified during the development of the ten mCDR options.

Category	**OAE**				**blueCDR**				**mCS**	
Option	3.1.1 Alkalinity-enhanced solution	3.1.2 $Ca(OH)_2$ along ship tracks	3.1.3 Coastal enhanced weathering	3.1.4 Electrolysis in desalination units	3.2.1 Kelp forest establishment	3.2.1 Mangrove (re)establishment	3.2.3 Artificial upwelling	3.2.4 Sargassum farming and sinking	3.3.1 Macroalgae farming for biomethane	3.3.2 Carbon storage via mineral trapping
Bottleneck factor for reaching 10Mt CO2 per year removal capacity (current factor restricting further upscaling of the option is marked with *)										
Infrastructure/Technology/TRL	TRL=3. Electrolysis technology for commercial usage.*	TRL=3. Installation of tanks, pumping and piping systems on ships.*	TRL=5. Transport, grinding and distribution of minerals at coastline.*	TRL=3. Electrolysis technology for commercial usage.*			TRL=2. Pipe efficiency under development.*	TRL=2. Upwelling infrastructure under development.*	TRL=5. Farming infrastructure in the open ocean.*	TRL=3-4. Infrastructure to capture, transport and inject CO_2 has to be built.*
Land/sea area demand	Limited area for implementation and its possible conflict with marine protected areas and other uses.* For 3.1.4 there is possible conflict with space on land (safe storage of waste product HCl).				Possible conflict with marine protected areas. * Area availability for creation of suitable substrate.*	Possible conflict with other land or sea area usage.*			High area demand and possible conflict with marine protected areas and other uses *	Area demand on land for DACC facilities.
Material demand	Mining and production capacity could restrict further scaling up. *					Large scale supply of propagules and seedlings for implementation.				Material needed to build and run DACC facilities to achieve large scale capture.
Clean Energy Demand	Decarbonation of the slaked lime production reduces the CDR efficiency. Emission during mining, transportation, and deployment reduces the CDR efficiency			Availability of renewable energy is crucial for this option to be viable.*				Off-shore renewable energy (eg. floating solar) still under development.		High energy demand for DACC.
Research gap/Uncertainty										
Environmental effect (+/-)	Unclear effects of higher alkalinity and temporal increase of water parameters (e.g., pH, nutrient level, trace metal, and salinity) on marine life.				Increases diversity in established areas. Offering shelter for fish, invertebrates, birds, mammals. Establishment of an alternative ecosystem. Erosion protection		Unknown.		Unknown.	
Net CDR effectiveness	Alkalinity injection rate and dissolution kinetics need further research (linked to area demand) to prevent secondary precipitation. Long term fate of sequestered carbon is uncertain. For 3.1.3 option implementation of CCS for the lime production. Method efficiency without a low carbon energy source.						Method efficiency needs more research.	Fate of sunken biomass in the deep sea.	Method efficiency needs more research.	Method efficiency without a low carbon energy source.
MRV	Not established yet.					High effort due to the vast area.	Not established yet			
Cost	No pilot plant available.			Cost of electrolysis technology at			Upwelling pipe cost uncertain.			No pilot projects exist, which makes

				commercial level						storage cost estimates uncertain.
Durability	Long-term stability of added alkalinity.		Keeping the weathering material within the reactive (wave) zone.	Long-term stability of added alkalinity.	Long-term fate of the sequestered carbon is uncertain.	Long-term stability of stored carbon depends on the system's stability (subject to climatic changes and human activities).		Depends on the pre-treatment of the biomass before sinking and the remineralization rate at the deep sea.		Long-term evolution of pore space and permeability.
Other	Safe disposal of waste.			Safe storage of waste product HCl.	Uncertainty in the area estimation.	Uncertainty in area estimates (strong local variations).	Permits to operate in international waters.	Permits to operate in international waters.	Macroalgae productivity in the region.	DACC capacity dependency.

4.4 Limitation of this approach - Considering economics, ethics, acceptance, and legality of mCDR collection

Our focus lies on questions of effectiveness, scalability, and technological feasibility combined with some information on costs and environmental effects. Yet, there are other important questions that arise about these mCDR options and new technologies and practices. Even though an in-depth assessment is beyond the scope of this study, we want to briefly highlight four aspects we deem to be particularly pertinent for the potential deployment of mCDR or mCS: the economics, ethical arguments for or against deployment, societal acceptability, and legality.

The cost estimates for early stage deployment or piloting, we can provide here vary widely between the different mCDR options. Since many concepts are not yet implemented at scale, and/or have a rather low TRL, there are considerable uncertainties associated with these cost estimates. The ranges of the estimates for operative costs are substantial across different studies (NAS, 2021). Furthermore, when evaluating economic aspects of mCDR methods, it is necessary to go beyond operative cost assessments based on current prices and also account for price effects after a large-scale roll-out. For example an increased demand for certain input materials will increase the price of these materials, thus affect the removal costs and the relative price for the mCDR option compared to other emissions reduction and CDR options and thus, the overall costs for reaching national climate targets (Klepper & Rickels, 2012). Other factors such as learning-by-doing, the permanence of CO_2-storage, and the cost of negative side-effects and the value of co-benefits should also be considered (Rickels, 2023). An integrated economic analysis of mCDR deployment scenarios is urgently needed, but beyond the scope of this work.

Ethical convictions, namely on the impermissibility of letting people suffer the full consequences of unabated climate change, are a major part of what motivates interest in CDR. Implementation scenarios of CDR options can be evaluated from an ethical perspective, for example, looking at their impact on people and the natural world as well as their governance (Heyward, 2019). This paper affirms the value of these considerations (Lenzi et al., 2018) but restricts itself to assessing the techno-environmental feasibility and effectiveness of certain CDR options. This is a paper about what could potentially be done – it paves the way for later questions about what should be done (Zimm et al., 2024). In this context, one important issue that needs to be briefly discussed here, is the question of the moral (im)permissibility of the inclusion of CDR options outside of Germany or its territorial waters. One could argue that CDR options tasked with counterbalancing German emissions should be deployed on German territory, and not 'outsourced' to other countries. We want to highlight that the ethical implications of the extraterritorial use of CDR will heavily depend on the specific characteristics of the projects in question. Disregarding side effects on local people or the local environment abroad because they would happen 'somewhere else', would clearly be morally problematic. However, if the options in question receive the informed consent of the local inhabitants, and especially those potentially affected (Preston, 2013), we deem it an open question whether extraterritorial CDR, potentially in areas where its effectiveness is much higher than in Germany, could be morally permissible. While an exhaustive discussion of this issue is beyond the scope of the paper, we do see the need to discuss this further and hope to provide input for these debates.

Any CDR implementation happens within societal context, which involves opinions of the general public and of local communities affected by the measure (Chen et al., 2015; Segreto et al., 2020). Concerns that remain unaddressed and voices that remain unheard can negatively influence the socio-political feasibility of implementation (Wüstenhagen et al., 2007). Considering local knowledge and contexts such as governance structures, past experiences, and enabling participation through benefit-sharing on the ground can increase the chances for long-term success (Merk et al., 2022). Ideally, this would require time and financial investment prior to starting the project to organize participatory engagement workshops and information sessions to enable affected communities to provide input on project siting and planning processes (Satterfield et al., 2023). Societal engagement in the project planning process needs to be built on trust, which can be gained by adhering to norms of procedural justice like transparency and fair participation (Heyward, 2019). This starts with the transparent communication about moral, social, economic and environmental risks and benefits and the possibility to participate in decision-making processes. While our analysis strives to make basic risks and benefits transparent, the development of tools for co-producing knowledge (Norström et al., 2020, Satterfield et al. 2023) and for supporting informed decisions (Nanz & Fritsche, 2012) are beyond the scope of this paper.

Turning to questions of legality, mCDR deployment raises a dilemma. While mCDR poses immediate risks, renouncing to deploy it may leave climate change unabated and create risks in the future. Delayed emission reductions reinforce our dependency on mCDR to reach the 2100 target of 1.5°C of global warming and will exacerbate the sense of urgency in choosing the lesser evil. This ethical dilemma is naturally reflected in the applicable laws. On the one hand, 'traditional' environmental law discourages any activity that may have adverse effects on the environment. On the other hand, climate change law, which sets ambitious temperature goals, arguably supports the enhancement of sinks and reservoirs. The precautionary principle for instance can be interpreted to either prohibit mCDR as a precaution for safeguarding the integrity of marine ecosystems, an understanding that seems to be envisaged by the Convention on Biodiversity. At the same time, it can also be understood as encouraging, or even requiring, the implementation of mCDR options in light of the consequences of unabated climate change as established by Article 3 of the UNFCCC (Tedsen & Homann, 2013). Contemporary international law therefore needs to reposition itself in order to adapt to this new, more complex reality in which the status quo may no longer be the safest choice. In that regard, the 2009 amendment of the London Protocol to allow for the geological sequestration of CO_2 and the 2013 amendment on marine geoengineering demonstrate the ability of international law to evolve. At the German level, current legislation, written with strong environmental concerns in mind, act as showstoppers for the deployment, and even research, of mCDR (Ginzky et al., 2011; UBA, 2023). Developments on the matter of mCDR at the international and European levels could thus provide guidance for an innovative interpretation of the precautionary principle in which research is enabled and risks are controlled through a regime of safeguards.

5 Conclusion and Outlook

Our study represents the first attempt at developing German site-specific CDR options with storage or sequestration in the marine environment. We challenged the mCDR options to reach a scale of 10 Mt CO_2 yr^{-1} removal, which would represent a substantial contribution to Germany's net-zero goal by counterbalancing projected residual emissions. This approach allowed us to compare mCDR options on the same scale and in their actual context of implementation, thereby providing a more policy-relevant evaluation of the associated area, energy, and resource demands.

We find that six out of the ten options considered in this study could potentially reach an annual removal rate of 10 Mt CO_2. Among them, three appear feasible within Germany: electrolytic production and addition of alkalinity-enhanced solution from silicate rock; production and spread of $Ca(OH)_2$ along ship tracks in the North Sea, and biomass from macroalgae farming for biomethane production combined with carbon storage in saline aquifers in the North Sea. This study does not exhaust all possible mCDR options in Germany nor assess their theoretical maximum potential for Germany, but with six options passing the 10 Mt CO_2 removal yr^{-1} benchmark, we could envision that mCDR can provide a significant contribution to carbon removal, and should be considered in the option portfolio for German net-zero.

However, we also identified a multitude of bottlenecks concerning mCDR options for annual 10 Mt CO_2 removal, ranging from geophysical constraints to current material and clean energy availability to the current technology and infrastructure capacity (see Table 2). For example, with the exception of kelp forest management, the CDR potential of these options cannot currently be fully determined due to their low technological maturity. Remaining research questions are method-specific: for OAE options, research concerning the understanding of the dissolution process of implemented materials is needed, which in turn will impact the spreading mechanisms, thereby impacting area, resource, and energy demands. For OAE and blueCDR options, one of the biggest remaining questions concerns the monitoring and verification of carbon fluxes. For the geological storage of carbon in the German EEZ, pilot studies are required to explore potential storage sites and determine achievable removal rates. For all of these options, thorough cost analyses along with life-cycle assessments are necessary to provide a realistic assessment of investment and market costs.

This study intends to provide a collection of mCDR options as the basis for more thorough assessments of mCDR options developed by Germany, both within and outside of German borders. Ideally, these future assessments will be supported by more comprehensive implementation scenarios that include evaluations of social, ethical, and political impacts. In addition, multiple CDR options should be jointly considered for potential synergies and trade-offs, especially regarding additivity and concomitant side-effects, to better characterize possible future implementation scenarios.

Our exploration of mCDR options on a 10 Mt CO2 yr^{-1} removal scale has revealed a multitude of limitations, bottlenecks, and uncertainties. We believe more of such assessments are needed to bring the expectations about CDR option down-to-earth (Dean et al., 2021), because over-optimistic or untested assumptions about large-scale CDR implementation should not serve as a reason to delay emissions reduction by suggesting it is possible to "emit now and remove later" (Fuss et al., 2014; Williamson, 2016).

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Data Availability Statement

No new data was used in the preparation of this manuscript. For the option 3.1.1, data is available through BGR 2021, BMWK 2023, Bockmon & Dickson 2015, du Bois et al. 2020, Dormann 2023, Foteinis et al. 2022, Fraunhofer 2021, Hartmann et al. 2023, Hoppema 1990, House et al. 2007, Moras et al. 2022, Rau et al. 2013 & 2018, Sonnichsen et al. 2023, Sündermann & Pohlmann 2011, and Wayman et al. 2021. For the option 3.1.2, data is available through BGR 2021, BMWK 2023, Caserini et al. 2021, Ejenstam 2010, Gunson 2013, Kearns et al. 2021, Kellenberger et al. 2007, Locke et al. 2009, Macovei et al., 2021b & 2021a, McLaren 2012, Nilsson et al. 2018, Polo 2012, Renforth et al. 2013, Schorcht et al. 2013, Tarantola & Gentile 2021, Tosun & Konak 2015, US Department of Energy 2013, and Xu et al. 2014. For the option 3.1.3, data is available through Beerling et al. 2020, BGR 2021, BMDV 2016, Doney 2010, Flipkens et al. 2021, Foteinis et al. 2022, Fraunhofer 2021, GESAMP 2019, Hangx & Spiers 2009, House et al. 2007, Kroeker et al. 2013, Montserrat et al. 2017, and NAS 2021. For option 3.1.4, data is available through Ahmed & Anwar 2012, Al-Anzi et al. 2021, Albright et al. 2016, Anderson & Dyrssen 1994, Bach et al. 2019, Cripps et al. 2013, DEWA 2022, Dickson & Et 2007, Du et al. 2018, Ferderer et al. 2022, García-Rodríguez & Gómez-Camacho 2001, Gately et al. 2023, Ghaffour et al. 2015, Gordon 2019, Gude 2016, Hartmann et al. 2023, House et al. 2007, ITA group 2021, Jones et al. 2019, Kumar et al. 2019, Langer et al. 2006, Lattemann & Höpner 2008, Missimer & Maliva 2018, Paleologos et al. 2018, Qasim et al. 2019, Rau et al. 2018, Renforth & Henderson 2017, Roberts et al. 2010, Techsci Research 2023, UAE embassy 2023, and UAE Energy Report 2015. For option 3.2.1, data is available through Fredriksen et al. 2020, Paris et al. 2022, Schubert et al. 2016, Siegel et al. 2021, and Smale et al. 2020. For option 3.2.2, data is available through Cameron et al. 2019, Castro et al. 2022, Chowdhury et al. 2018, Kayalvizhi & Kathiresan 2019, Sasmito et al. 2023, Theuerkauff et al. 2020, and Van Zanten et al., 2021. For option 3.2.3, data is available through Dutreuil et al. 2009, Jürchott et al. 2023, Keller et al. 2014, NAS 2021, Oschlies et al. 2010b, Palter et al. 2023, Siegel et al. 2021, and Williamson et al. 2012. For option 3.2.4, data is available through Buck & Langan 2017, Buck-Wiese et al. 2023, Carpenter 1972, Casazza & Ross 2008, Chereau 2019, Garcia et al. 2013, Howard & Menzies 1969, Johnson & Decicco 1983, Lapointe et al. 2021, Nagare et al. 2012, Powers et al. 2019, Stommel et al. 1956, and Wang et al. 2018. For option 3.3.1, data is available through Alcalde et al. 2018, Arts et al. 2004, Barbot et al. 2016, Berger et al. 2023, Blomberg et al. 2021, Borchers et al. 2022, Bruton et al. 2009, BSH 2009, Buck et al. 2018, Buck & Buchholz 2004, CESNI 2020, Chen et al. 2015, Daniel-Gromke et al. 2018, EBA 2023, Fernand et al. 2017, FNR 2019, Fuss et al. 2018, Gao et al. 2020, Hughes et al. 2012, Jakobsen et al. 2017, Jia et al. 2022, Kaltschmitt et al. 2016, Kearns et al., 2021, Kerrison et al. 2015, Kim et al. 2017, Leedham et al. 2013, Lin et al. 2019, Lumley 2001, Malischek & McCulloch 2021, Marinho et al. 2015, Net Zero 2050 Team 2021, Raven 2017, Tegtmeier et al. 2012, Vangkilde-Pedersen et al. 2009, Weinberger et al. 2020, Wollnik et al. 2023, and Wu et al. 2023. For option 3.3.2, data is available through Aspelund & Jordal 2007, Borchers et al. 2022, BSH 2023, Chatterjee & Huang 2020, Chen & Morosuk 2021, Eiken et al. 2019, Fasihi et al. 2019, Flaathen et al. 2009, Furre et al. 2017, Fuss et al. 2018, Harris & Higgins 2008, Heß et al. 2020, IEA 2022, Keith et al. 2018, Matter et al. 2009, McGrail et al. 2014, NPD 2019, Øi et al. 2016, Parkhurst et al. 1999, Planke et al. 2021, Realmonte et al. 2019 & 2020, Reyes-Lúa et al. 2021, Roussanaly & Anantharaman 2017, Smith et al. 2016, Snæbjörnsdóttir et al. 2020, Socolow et al. 2011, Viebahn et al. 2019, Weiss 1974, Wiese et al. 2008, and ZEP 2019.

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Earth's Future

Supporting Information for

Exploring site-specific carbon dioxide removal options with storage or sequestration in the marine environment - The 10 Mt CO_2 yr^{-1} removal challenge for Germany

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1. Contents of this file

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2. Introduction

This document includes the tables of categories and parameters used in the fact sheet for the generation of mCDR options with a detailed explanation of the estimates used in this study. The estimates are based on current knowledge and discussed for an up to date implementation plan.
The mCDR were scaled to 10 Mt CO_2 removal per year goal, and for those that do not reach such scale, the maximum CO_2 removal per year was provided. The estimates were carried out assuming linear scalability to 10 Mt CO_2 removal potentials. The economic, legal, societal or political aspects were not considered for the development of the options.

TRL	Scale	EC HORIZON 2020 Work Programme	Adaptation
1	paper	Observation and description of the functional principle;	Concepts are defined, but are not proven yet
2	paper	Description of the application of a technology;	
3	laboratory	Demonstration of the functional capability of a technology;	Individual, relevant components are missing
4	laboratory	Experimental setup in the laboratory;	
5	demonstration	Experimental setup in deployment environment;	Most components are proven, but not yet combined
6	demonstration	Prototype in deployment environment;	
7	pilot	Prototype in use;	All components are proven, but not yet combined
8	pilot	Qualified system with proof of functional capability in use;	
9	full, market roll-out	Qualified system with proof of successful deployment.	All elements commercially available, value chain technically proven

Table S2 Definition of Technology Readiness Levels according to Horizon2020 (European Commission, 2014)

3 mCDR options

3.1 Ocean Alkalinity Enhancement

Here we provide schematic drawings (Figure S3.1.1 and S3.1.2), tables of categories and parameters (Table S3.1.1- S3.1.4) and extended explanation of the estimates for the four ocean alkalinity enhancement options described in this study.

3.1.1 Electrolytic production and addition of alkalinity-enhanced solution from silicate rock on the German North Sea coast

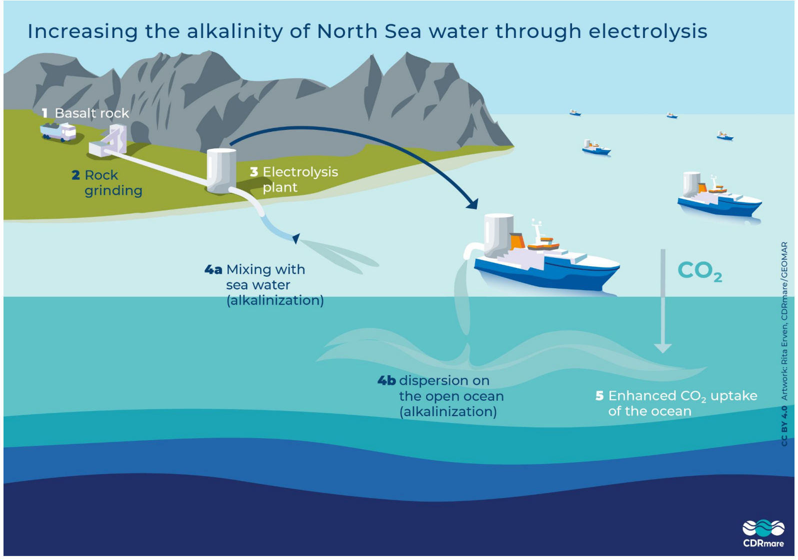

Figure S3.1.1 Schematic drawing of electrolytic production and addition of pH-enhanced solution from silicate rock on the German North Sea coast: (1) the basalt rocks are extracted from the mining area, (2) then the basalt rocks are grinded on site, (3) the electrolysis is added in sea water in the presence of basalt powder, (4a) resulting solution is mixed with seawater on the coast, (4b) the resulting solution can also be spread on the open ocean, (5) the alkalinity-enhanced water can sequester CO_2.

The global potential of electrochemical processes as a feasible approach to mCDR is estimated to be 0.1-1 Gt CO_2 yr^{-1}, due to the limitation of energy and water processing capacity (NAS, 2021).

The reaction we used in this option is from Rau et al. (2013) Eq. 1:

$$2CO_2 + 2H_2O + MgSiO_3 + Na_2SO_4 + V_{DC} \rightarrow$$
$$H_2 + 0.5O_2 + MgSO_4 + 2NaHCO_3 + SiO_2 \quad \text{(Eq. 3.1.1a)}$$

where Na_2SO_4 is added to deionized water to model the treated sea water. V_{DC} is the direct current voltage.

<u>Calculation of sea surface area demand:</u>

When dispersing the alkaline solutions, regardless of whether through a pipe outlet at the coast or ship on their offshore route, there is a minimal area demand for the alkalinity to dilute in order to prevent spontaneous precipitation. While it is not clear yet what the upper limit of the alkalinity is in the nature, lab experiments suggest that inorganic precipitation would appear when alkalinity increases for 250-600 µmol/L for unequilibrated alkaline solution addition (Hartmann et al., 2023; Moras et al., 2022). Considering the middle value of the estimation (425 µmol/L), and the annual average mixing layer depth (30 m; Sündermann and Pohlmann, 2011) of the southern part of the North Sea into the following equation:

$$D_{mix}\ S_{dis}\ A_{Lim\text{-}add}=A_{T\text{-}add} \quad \text{(Eq. 3.1.1b)},$$

where D_{mix} is the mixing layer depth, S_{dis} is the area for alkalinity dispersal, $A_{Lim\text{-}add}$ is the upper limit for alkalinity addition, and $A_{T\text{-}add}$ is the total alkalinity added. Hence , and the area needed for the dispersal of alkalinity is around 18,000 km^2 (0.23 Tmol/ (425 µmol/L *30m)).

The North Sea has a volume of 54,000 km^3 with an outflow of 2 Sv (2 M m^3/s, (Sündermann & Pohlmann, 2011). The water turnover then takes 0.86 yr (54, 000 Giga m^3/ 2 M m^3/s =27 M s= 312.5 days). This means that the entire water of the North Sea is renewed every 0.86 years. The German EEZ in the North Sea is 28,500 km^2. Hence, every year, there will be 33,140 (28,500/ 0.86) km^2 of "fresh" sea surface water.

This option with 10 Mt $CO_2\ yr^{-1}$ scale will utilize about 55 % of the "fresh" sea surface water German EEZ in the North Sea (18000 km^2/ 33140 km^2), which translates to 55 % of the German EEZ in the North Sea, which is 15,500 km^2. When regulating the maximum of alkalinity in addition to 250 µmol/L only, the area would be 26,400 km^2, 93% of the EEZ in the North Sea.

Note that, for our calculation, it is assumed that the whole North Sea has the same turnover rate, which fits our purpose of scoping relevant limitation factors for the option. However, it has been demonstrated by past studies for radioactive contaminants tracing in the North Sea (e.g., du Bois et al., 2020), that the differences in the regional turnover may vary and German EEZ has a higher turnover rate compared to the rest of the North Sea. This implies a higher capacity for alkalinity addition, but even with our conservative estimation, alkalinity enhancement does already pass the bar of 10 mt CO_2 removal per year. In this study, we assumed that Germany is the country that is actively deploying mCDRs in the region, but it might not be realistic that Germany is the only country in the North Sea region that is actively involved. If other countries, e.g., UK or Holland, would add alkalinity into the North Sea at the same time, due to the current directions, German EEZ may not have "Fresh" water free from alkalinity additions and a conservative estimation based on the turnover of the whole region could be more plausible under this scenario.

Estimates of resources demand for the CO_2 removal:

For each ton of CO_2 removal, 3 t of basalt and around 1.9 MWh electricity are consumed (including crushing of rocks, excluding transportation of material and the mining; Rau et al. 2013; House et al. 2007).

The current mining capacity of basalt in Germany is 32 Mt rock per year (BGR, 2021), and renewable electricity generation in Germany in the year 2020 amounts to around 250 TWh yr^{-1} (BMWK, 2021).

Mining water requirement varies according to the used rocks and it demands 210 L kg^{-1} for cement, 0.45 L kg^{-1} for lime, 0.21 L kg^{-1} for crushed limestone. This water requirement includes both the process of water usage and the pollution of the water body (not to cross the most restricted threshold among EU, Canada and US regulation; Gerbens-Leenes et al., 2018). However, a recent study in Qatar suggests that the number can be as small as 0.007 L kg^{-1} for limestone (Wayman et al. 2021)

Assuming that 1 mol of CO_2 equals 1 mol sodium hydroxide, if we want to reach 10 Mt CO_2 removal (equal to 0.23 Tmol), 0.23 Tmol of sodium hydroxide needs to be produced. Considering that the sodium chloride concentration in the North Sea near Emden is 420 mol/m^3 (31 ppm, (Dormann, 2023); and assuming 31% is sodium), we would need about 548 Mt (0.5 km^3) of seawater, about 10% of the total abstraction of ground water in Germany in 2019 (5.35 billion m^3/ 5.35 km^3, BGR, 2021)). Since the volume of the North Sea is 54 000 km^3, it is around 0.001% of the North Sea water.

Considering the relative demands for capacities, and the undergoing expansion of renewables in Germany, a likely bottleneck could be the mining capacity of basalt and the transportation of materials from the mining sites (e.g., north Bavaria) to the coastal region (>700 km). As Germany aims to increase the share of green energy to 80-95% in the year 2050, the storage capacity of the power grid is essential, considering the fluctuation of solar and wind energy. In 2020, there are a number of power-to-gas (hydrogen) pilot plants operating in Germany and a 100 MW plant is planned in Lower Saxony. If electrolysis-based alkalinity enhancement were to be included in the plan for energy storage infrastructure construction (gas storage, fuel cell transportation, and energy generation) near the coastal region, this would reduce the overall investment for the deployment of this mCDR method.

MRV:

0.23 T mol of CO_2 translates to 0.23 T mol HCO_3^-, hence if distributed evenly in the North Sea, the change of alkalinity would be 4.3 µmol L^{-1}. (0.23 T mol / 54,000 km^3 = 4.3 µmol L^{-1}). This is in the same magnitude of the accuracy of alkalinity measurements in the lab (2-10 µmol L^{-1}; (Bockmon & Dickson, 2015)). However, this is 4 times smaller than the accuracy of on-site sensors (16 µmol/L; Sonnichsen et al., 2023).

On top of that, the North Sea has a quick turnover rate of 0.86 yr (see above), and the seasonal variation of alkalinity can be in the 100 µmol L^{-1} range (Hoppema,1990), which means that measuring the change in alkalinity can be even more challenging.

Cost estimates and energy demand:

The conversion between US dollar and Euro uses the exchange rate in 2023 (1 $ = 0.93 €). The cost for 10 Mt CO_2 per year operation includes an initial investment cost and maintenance cost (mining/grinding, transportation, electricity and human labor). The cost of each section is detailed below. For the first investment, the cost amounts to 2.6 billion € for the 30 Mt mining operation (already existing in Germany).

For the electrolysis facility of capacity of 0.11 Mt hydrogen per year we use estimates from already existing projects such as 2 Mt hydrogen per year HYRASIA ONE (Kazakhstan, http://hyrasia.energy/), with a cost of 40 billion € (20 times larger than what we need), and the 2GW hydrogen projection in Neom with a cost of 7.8 billion € (https://www.neom.com/en-us/newsroom/neom-green-hydrogen-investment).

The cost for maintenance includes the mining and grinding, the transportation of the goods, the electricity for electrolysis and the salary for the employees.

For mining and grinding, we estimated between 9 to 18 million € for 30 Mt of rocks/material. The energy required per ton of rock for mining and grinding is 7 kWh t^{-1} and 0.84 kWh t^{-1}, respectively. In the case of reaching a size of 100 µm, the energy for grinding has an increase of 24.5 kWh t^{-1} (Foteinis et al., 2022).

Assuming that all operation can use electricity, the electricity consumption for 30 Mt is 234 * 10^6 kWh (7.8kWh t^{-1} *30 Mt= 234 * 10^6 kWh) and 969 * 10^6 kWh for reaching 100 µm size.

The energy cost ranges from 0.04 to 0.08 € kWh^{-1}, which would lead to an overall cost of 9-18 million € for 30 Mt for mining/grinding in this operation.

The cost for transportation of 30Mt of rock for 700 km by ships (cheapest solution in Germany) would be 0.0011 € t^{-1} km^{-1} * 30 Mt *700 km=0.02 billion €.

Electricity in the facility contains the electricity for electrolysis and pumping systems. The wind energy production cost is 0.04 -0.08 € kWh^{-1} (Fraunhofer, 2021, https://www.ise.fraunhofer.de/en/publications/studies/cost-of-electricity.html). If all the electricity is from wind, then the cost for the electrolysis would be 0.76 -1.5 billion € per year (0.04-0.08 € kWh^{-1} * 19TWh). For simplification, we assume that half of this electricity can be recycled (e.g., produce electricity with the produced hydrogen) and feed back to the electrolysis. Then, the cost would be reduced to 0.38-0.75 billion € per year. If the hydrogen is sold directly as a by-product, this calculation would depend on the market price of hydrogen. The pumping system needs about 0.7 kWh electricity for every 1 m^3 of seawater (number from University of Houston, accessible at: *https://uh.edu/uh-energy/educational-programs/tieep/content/energy-recovery-presentation-2020-water-forum.pdf*). The cost of pumping and filtration of 548 Mt seawater (1.025 t m^{-3}) would cost 0.02-0.03 billion € per year.

The number of employees involved in this operation comprehends about 50 employees for different facilities, plus several employees in the mining. We assume that the operation would have 50 - 230 people. The average salary in 2023 in Germany is 48 k € /year, therefore the total cost would sum up to 0.002-0.01 billion € per year.

If we assume a cost for 30 year of usage, the overall estimated cost would be 0.78-1.2 billion € yr^{-1} (annual invest cost = 0.35 billion € yr^{-1} and annual maintenance cost = 0.43-0.82 billion € yr^{-1}), which in turns represents 78-120 € per ton of CO_2 removed. Our estimate is in agreement with previous estimates of 17-160 $ per tCO_2 by Rau et al., (2018).

If released to the North Sea, the natural circulation and mixing may transport the alkalinity enhanced water to the waters of neighbouring countries, for the predominant circulation patterns that would be mainly Denmark at first and later eventually to the whole region. Hence, the impact on downstream ecosystems and possible alkalinization efforts needs to be studied and monitored.

Category	**Parameter**	**for 10 Mt / year operation**
Option description	Maturity level (Technology readiness level)	Electrolysis in sea water has been conducted in labs. Hence we assess a TRL of 3.
	Infrastructure	**Requirement from material abstraction (capacities described in demand/Input cells):**

		For mining, we need quarries near the waterway, such as the ones near Frankfurt am Main. For the seawater requirement, we need pumping systems on the coast/ onshore platform that are similar to the desalination plants. In addition, renewable energy sources that have off-peak energy, such as offshore wind farms, are needed. **Transportation of material (what is needed and their capacities):** Germany waterways have a capacity of 65 Gt-km per year (BMDV, 2016: https://bmdv.bund.de/SharedDocs/EN/Articles/WS/waterways-as-transport-routes.html). From Frankfurt am Main to Emden is about 600 km on the waterway, which means about 18 B t-km, about 28% of the waterway capacity. The Port of Emden had a turnover of 4.3 Mt in 2022 (Seaports, 2023: https://www.seaports.de/zahlen-daten-fakten/), for a yearly handling of 30 Mt rocks, the port of Emden would need to be expanded, or nearby ports need to be used for such an operation. A pumping system similar to a desalination plant or sewage treatment plant is needed for the water intake and outflow in the electrolysis facility. The sewage treatment plant in Hamburg treats 151 Mt of water per year (Dstatis, 2023:https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Umwelt/Wasserwirtschaft/_inhalt.html). Here, we would need about 3 plants of that scale.
	Biophysical conditions	High turnover of seawater, so that the alkalinity-enhanced water will be diluted quickly. High mixing helps the alkalinity-enhance water to equilibrate with the air.
	Location	Mining in midwest Germany (assuming near Frankfurt am Main) Energy extraction in the North Sea Facility in North Germany (assuming near Emden) CO_2 uptake in the North Sea
Demand/Input	Area/land	3,120 m^2 for mining (Foteinis et al., 2022) and about 15,500 km^2 sea surface area for dilution of alkalinity (55% of the German EEZ in the North Sea)
	Material/resources	Basalt rock 30 Mt per year
	Energy demand	19.32 Twh electricity / year (including electrolysis, mining, and grinding, excluding the energy output)
	Water demand	460 Mt seawater/ year
Output	CO_2 removal potential	10Mt CO_2/ year
	By-products	9.5 Twh energy in the form of hydrogen
	Energy output	9.5 Twh energy in the form of hydrogen
Environmental impacts	Soils/sediment	Possible increase of heavy metal in the sediments in the coastal region
	Water	Possible pollution at the mining sites affecting the groundwater. Potential increase of heavy metal concentration in the North Sea, if the rocks has high content of heavy metals

	Air	Possible fine dust pollution near the mining sites
	Noise	Constraint at the mining sites
	Ecosystem	Negative impact: - possible accumulation of heavy metals in the coastal ecosystem - shifts in the food web due to addition of nutrients such as iron and silicate if using basalt rock Positive impact: - stabilize the pH and potentially help maintain the shellfish fisheries in the North Sea. - potential increases of the primary production in the North Sea, with consequences in improving the fishery capacity in the North Sea.
Economic parameters	CO_2 removal costs	780-1200 Mio. € yr^{-1}
	Investment intensity	10000 Mio. €
	Maintenance cost	430 -820 Mio. € yr^{-1}
	Monitoring, reporting and verification (MRV)	Unknown. Long term monitoring of the environmental parameters and ecosystem on site is needed, e.g., water quality monitoring for heavy metal and other pollutants, and also monitoring the health of species population for key species (fishery). Those monitoring efforts can be integrated into existing EU-wide monitoring networks. The verification of alkalinity enhancement is difficult due to the strong background signal of natural alkalinity variation, hence suitable models have to be in place for the continuing assessment in addition to on-site measurements.
Systemic parameters	max. CO_2 removal potential	11 Mt CO_2 per year if exhausting all current basalt productivity in Germany. Germany basalt output is 32 Mt per year (BGR, 2021)
	Permanence	CO_2 is stored in the form of bicarbonate in the seawater, expected to be stable in the time scale of 100,000 years.
	MRV capability	Monitoring networks in the North Sea are an international effort, and current water quality and fishery monitoring networks should be utilized. Operating at point location is possible to verify, but on a large scale, the change of alkalinity is at least two magnitudes too small to detect, hence ocean models are an important asset for the estimation of effectiveness.

Table S3.1.1 Table describing the categories and parameters for the electrolysis of basalt and alkalinity enhancement on the North Sea German coast.

3.1.2 Production and spread of $Ca(OH)_2$ along ship tracks in the North Sea

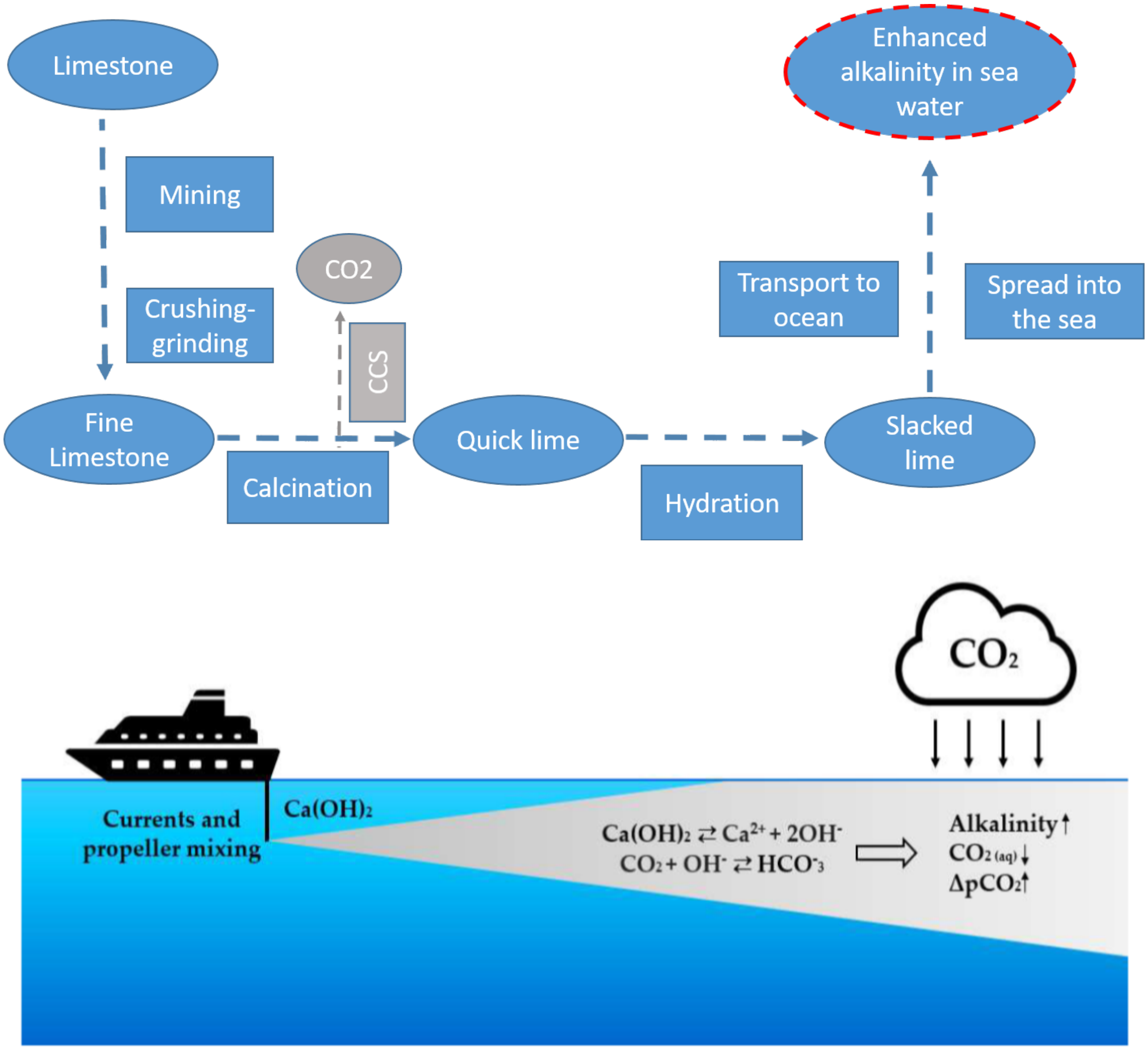

Figure S3.1.2 Option schematic drawing for production and spread of $Ca(OH)_2$ equilibrated solution along ship tracks (upper panel, adopted from Foteinis et al., 2022) and example of slaked lime discharge via ship and principal occurring phenomena in short time scale (lower panel, adopted from Tarantola & Gentile, 2021)

The spreading of $Ca(OH)_2$ (commonly named slaked lime) in seawater has been suggested to have a large potential for CO_2 removal from the atmosphere, as well as for mitigating ocean acidification and enhancing the net calcification of reefs (Albright et al., 2016). The traditional pathway for $Ca(OH)_2$ production starts from limestone ($CaCO_3$) mining and grinding, followed by calcination to quicklime (CaO), where CO_2 from $CaCO_3$ is released and the CaO is then hydrated to produce slaked lime.

Estimates for resources demand for the CO_2 removal:

According to (Foteinis et al., 2022), the amount of materials, water and electricity required by **every tonne of CO_2 sequestered** are detailed as follows:

Limestone and slaked lime: 1.79 t of limestone to be mined, crushed, calcined, hydrated into 1.321 t of slaked lime.

Electricity (descriptive):

- During the limestone mining phase, the percussion drill needs 2.92 kWh, excavators, bulldozers and trucks require 7.97 kWh, other machinery requires 1.67 kWh (US Department of Energy, 2013), which equals to a total of 12.56 kWh.
- During the limestone crushing and washing process, the cost of electricity includes primary and crushing of $4.11*10^{-1}$ kWh and 1.09 kWh, separately (Tosun & Konak, 2015), screens and conveyor belt of $8.60*10^{-2}$kWh (US Department of Energy, 2013), Tertiary crushing/ Grinding (100 μm) of 41.9 kWh (Renforth et al., 2013).
- During the quicklime production process, the costs are: calcination electricity input of 20 kWh (EuLA, 2014), air separation of 72.8 kWh (Renforth et al., 2013), calcination heat input of 1180 kWh (EuLA, 2014), CO_2 purification of 90.1 kWh (Xu et al., 2014) and CO_2 compression of 84.7 kWh (Renforth et al., 2013).
- During the hydrated lime production, the energy consumption is 7.66 kWh according to (Schorcht et al., 2013).
- During the hydrated lime transportation phase, the energy consumption of Truck loading is 2.94 kWh, the ship loading is 2.94 kWh, the dockside operation is 6.97 kWh, the distribution to the ocean is 2.94 kWh. All the estimations are based on (Renforth et al., 2013).

The sum of all the above items are equal to a 1.53 MWh per ton of CO_2 removal.

Water:
Water consumption includes limestone mining of $3.57*10^{-1}$ m^3 (Gunson, 2013), limestone crushing and washing of $3.31*10^{-4}$ 4 m^3 (Kellenberger et al., 2007), hydrated lime production of $3.21*10^{-1}$ m^3 (Ejenstam, 2010), which is a total of 0.678 m^3 per ton of CO_2 removal.

If all those numbers are scaled to 10 Mt CO_2 removal, 17.9 Mt of limestone is necessary, which corresponds to 13.21 Mt of slaked lime, $1.53*\ 10^{10}$ kWh (equal to 15.27 TWh) electricity and 6.78 Mt of water.

According to BGR (2021), the current annual production of limestone in Germany is ~56 Mt per year with ~27 Mt used in the limestone industry (burned lime CaO and limestone products) and the production capacity could easily be enhanced depending on permissions for quarries and social acceptance. The renewable electricity generation in Germany in the year 2020 amounts to around 250 $TWh_e yr^{-1}$ (BMWK, 2021). The required water is considered as unlimited. If we scale all these required resources from Germany up to the whole of Europe, then we will have enough raw materials, water and electricity for the 10Mt CO_2 removal target.

Land-sea area:

The land use in limestone mining and lime production consists of land use change: transformation from forest ($1.16*10^{-5}5$ m^2), transformation to mineral extraction site ($1.16*10^{-5}$ m^2), recultivation ($1.16*10^{-5}$ m^2), and land use for mining ($1.51*10^{-4}$ m^2), which is in total of $18.58*10^{-5}$ m^2/tonne of CO_2 removal. This is corresponding to 1858 m^2 of land required for 10Mt CO_2 removal.

The ocean use is mainly related to lime dispersal. For the slaked lime dispersal in the North Sea, we constrain the dispersal within the German Exclusive economic zone (EEZ) area to avoid possible international conflict. According to the spatial planning ordinance for the German exclusive economic zone in the North Sea, only part of the German EEZ is designated for shipping (Nilsson et al., 2018). The needed area for spreading may vary due to the geophysical conditions of the area; here 15,500 km^2 in the North Sea EEZ is required based on the assumptions in 3.3.1, in order to avoid potential inorganic precipitation (adding more than 425 µmol/L) alkalinity locally.

Infrastructure:

Infrastructures regarding the lime production (limestone mining, comminution, calcination and hydration) are already existing in Germany as lime factories.

For lime spreading into the ocean, bulk carriers are immediately suitable for slaked lime discharge without major modifications needed, while container ships are less usable and would require significant changes in their structures and installation of appropriate tanks, pumping and piping systems.

More dedicated infrastructures should be installed at calling ports.

Cost estimates:

The conversion between dollar and Euro uses the exchange rate in 2023 (1 \$ = 0.93 €). The total cost is encompassed in three sections. The cost of each section is detailed below.

- Cost of lime production: the electricity required during the lime production is 1.51 MWh per ton of CO_2 removal (as summarized in the table S3.1.3). Scaling up to 10 Mt CO_2, the electricity needed in this section is 15.1 TWh. Considering the energy cost ranging from 0.04 to 0.08 €/kWh (same as option 3.1.1, from Fraunhofer, 2021), it leads to an overall cost of 0.6-1.2 b € for 10 Mt CO_2 removal.
- Cost of inland lime transportation: we assume an average on land transportation distance of 700 km, for a total quantity of lime of 13.21 Mt. The inland

transportation by ships (cheapest solution in Germany) price is estimated as 0.0011 €/t/km (Fichtner, see Supplementary Table "Technological Cost Estimation"). We therefore estimate the on land transportation is 0.0011 €/t/km * 13.21*10^6 t* 700 km=10.2 M €.

- Ship spreading of slaked lime cost: the cost of spreading lime into the ocean consists of two parts: the operating and capital expenditures (Tarantola & Gentile, 2021). The operating expenditure is defined as a continuous cost for running a system or a business, while the capital expenditure is the expense of providing durable parts for a product or system. The principal operating costs are crew salaries, fuel consumption, eventual maintenance or repairs, taxes related to the shipping duration and harbor fees, insurance and administration costs, cargo handling, and ground operations in port (Polo, 2012). The capital cost is generally split into two parts: bare erected costs, which include the cost of process equipment and needed infrastructures, and contingencies.

According to Tarantola and Gentile (2021), the total operating cost is within the range of 4.04~4.11 € per tCO_2, with the shipping operating cost varying within the range of 3.48~3.56 € per tCO_2, while the pumping operating cost ranging from 0.55 to 0.57 € per tCO_2. The total capital cost is ranging from 1.76 to 4.67 € per tCO_2, with the conditioning capital cost within the range of 0.83~4.67 € per tCO_2. If the dedicated fleets are used, then there is an additional vessel cost of 0.93 € per tCO_2. As a result, the total cost of SL spreading is ranging from 5.87 to 8.76 € per tCO_2. Scaling up to 10 Mt CO2, it requires 58.7~87.6M €.

- CCS cost: it should be noted that during the mining, processing and up to the spreading of lime, an amount of 449 kg CO_{2eq} is generated (Foteinis et al., 2022), in which the CCS should be considered. Here we consider the CCS the same with section 3.3.1, where the CO_2 is transported by pipeline to a geological formation in the seabed of the German Exclusive Economic Zone in the North Sea, where it is injected in saline aquifers for permanent storage.

The cost of CO_2 capture (maily purification, compression and air separation) are owing to their corresponding electricity consumption, which has already been included in the cost of lime production (Table S3.1.3). So here we only calculate the transportation on land with pipeline, the injection and storage.

The cost of: 1) transportation by pipeline to the offshore site is 9.3 € per tCO_2 assuming an average distance of 400 km from all major lime plants to the North Sea (Kearns et al., 2021). 2) CO_2 injection and storage (offshore): 18.6 € per tCO_2. 3) CO_2 monitoring program: 4.65 € per tCO_2

Scaling up to 10 Mt atmospheric CO_2 removal by ocean liming, there would a penalty of 449 kg CO_2eq*10 Mt=4.49 Mt produced and CCS needed. The corresponding cost should be (9.3 € + 18.6 € + 4.65 €)/tonne of CO_2 *4.49 Mt=146.15 M €.

In summary, if CCS is not included, the total cost is 0.6 - 1.2 b € + 10.2 M € + 58.7~87.6M € = 668.9~1297.8 M € (cost of lime production, inland lime transportation and ship spreading of slaked limeL, respectively), while if the CCS is included, the total cost is 668.9~1297.8 M € + 146.15 M € = 815.05~1443.95 M €.

Investment intensity:

In Germany, the lime factories already exist, so there is no need for the first investment regarding the lime production.

Regarding the discharge systems, the fixed costs are related to the capital expenditure, which consists of engines and pumps for water suction and slaked lime discharge, pipes and distribution lines, as well as dedicated tanks. In addition, a 10% contingencies value on the total capital cost is added. In (Caserini et al., 2019), a 25 years lifespan is considered. A summary of the total ship conditioning capital expenditure is given by Tarantola and Gentile, (2021) in their Table 3.5.

So the yearly investment regarding the ship dispersal is 1071200$/yr for a bulk carrier with a dwt of 75,000, which equals to 996216 €/yr. Assuming a cruising speed of 25km/h and an average discharge rate of 50 kg/s, an average length at sea of 181 days/yr, hence a carrier can discharge 0.78 Mt (50 * 24*3600 *181 kg) slaked lime per year. Since the specific CO_2 removed per slaked lime mass (1/1.321), in order to achieve a total of 10 Mt CO_2 removal, 13.2 Mt of slaked lime need to be discharged per year. Hence, a fleet of 17 (13.2 Mt/ 0.78 Mt) carriers is needed, and the cost per unit of CO_2 removed is 1.68 €. Scaling up to 10Mt CO_2 per year would be 16.8M €.

Maintenance cost:

The maintenance cost is mainly the cost including the production of lime (mining, grinding, calcination and hydration), the transportation and the transportation of the goods and the salary for the employees as mentioned in option 3.1.1.

For the lime production, it is estimated in the above as 0.6~1.2 b €. We assume the salaries of employees for the lime production is the same as estimated in option 3.1.1, which equals 2~10M €.

The transportation cost is 10.2 M €.

During the lime dispersal phase, the maintenance cost is mainly the operational cost, which is 4.04~4.11 €/tCO_2 * 10Mt CO_2=40.4~41.1 M €.

In total, the maintenance cost is 0.6~1.2 b € + 2~10M € + 10.2 M € + 40.4~41.1 M € = 652.6~1261.3 M €.

Monitoring system:
The monitoring of the ocean environmental change due to the lime spreading can be conducted through the existing Ship-of-Opportunity, FerryBox-integrated, membrane-based sensor measurements in the surface North Sea. The underway measuring instruments are equipped on repeating commercial vessels, which provide a cost-effective way to observe the surface ocean at a relatively large temporal resolution and spatial coverage (Macovei et al., 2021a,b). Besides the traditional oceanographic variables are measured, the carbon-related parameters (such as $p\mathrm{CO}_2$, pH, and alkalinity) and other biogeochemical variables (such as nutrient concentration, *chl-a*, phytoplankton biomass and oxygen) can be measured as well. Those methods succeeded to complement the limited observational capacity of scientific research cruises and fixed-point observatories in oceanic regions.

Environmental impact: Ocean liming might cause localized temporary pH and alkalinity spikes very shortly after the discharge (within several minutes), which might be ecotoxic and detrimental for the ecosystems (Locke et al., 2009).

Category	**Parameter**	**Description**
Option description	Maturity level (Technology readiness level)	Industrial processes of calcination ($CaCO_3$ + heat=> $CaO + CO_2$) and hydration ($CaO + H_2O$ => $Ca(OH)_2$+heat) are TRL 9 (Foteinis et al., 2022). There are still limiting factors that are not well examined, including the need for the capturing and storing the calcination's CO_2 emissions (Renforth et al., 2013) and the infrastructure (vessels) for lime spreading (Caserini et al., 2021). Therefore, the combined ocean liming system is at TRL 3-4 (McLaren, 2012).
	Infrastructure	**Requirement from material abstraction (capacities described in demand/Input cells):** ● Mining: quarries, quarry infrastructure, land, water, percussion drill, blasting, excavators, bulldozers ● Crushing and washing: screens and conveyor belt ● Calcination and hydration: shared with the infrastructure of limestone calcination (Foteinis et al., 2022). ● For the water requirement, we will need pumping systems for the water intake and outtake, or probably a combination with sewage treatment or desalination plant. **Transportation of material (what is needed and their capacities):** ● Transport from quarries to ports: ships (the cheapest) ● Ports: loading

		● Ship spreading: mainly container ships and bulk carriers
	Biophysical conditions	High mixing/advection rate to avoid too high concentration of alkalinity and pH level.
	Location	● Material mining and production is mainly in middle Germany (in Brandenburg, near Berlin), but might also extend to the other European countries around the North Sea for extra production. ● Storage of purified CO$_2$ in German North Sea sector, i.e., 150 km from Brunsbüttel (see also 3.1.1) ● Slaked lime spread in the North Sea via ship tracks, so CO$_2$ uptakes in the North Sea.
Demand/Input	Area/land	348 m^2 of land use change (transformation from forest, transformation to mineral extraction site and recultivation) and 1510 m^2 of land use for mining (occupation, mineral extraction) (according to (Foteinis et al., 2022), in total of 1858 m^2. Based on the area requirement in order to not bypass the alkalinity threshold (see 3.1.1), 15,500 km^2 of sea area is needed in the German EEZ.
	Material/resources	17.9 Mt of limestone, corresponding to 13.21 Mt of slaked lime (Foteinis et al., 2022).
	Energy demand	15.27 Twh electricity / year (including mining, crushing of rocks, calcination and hydration to produce lime as well as the transportation) (Foteinis et al., 2022).
	Water demand	6.78 Mt water (Foteinis et al. 2022)
Output	CO$_2$ removal potential	10 Mt per year
	By-products	unknow
	Energy output	333 kWh/tCO$_2$ energy in the form of low-grade heat is typically not recovered (Foteinis et al., 2022). Hence, the output is 0.
Environmental impacts	Soils/sediment	Possible increase of heavy metal in the sediments in the quarry areas
	Water	Possible pollution at the mining sites for the groundwater. Potential increase of heavy metal concentration in the North Sea, if the rocks have high content of heavy metals
	Air	Particulates emitted in a low population areas, 50% as >PM10, 45% as PM2.5-pm10, and 5% as < PM2.5 (Kellenberger et al., 2007)
	Noise	Constraint at the mining sites and no significant additional noise at the shipping lane is expected.

	Ecosystem	Very high alkalinity and/or pH levels in the wake of the ship shortly after the spreading (Caserini et al., 2021).
Economic parameters	CO_2 removal costs	815.05~1443.95 M € if CCS is considered.
	Investment intensity	16.8M € for 10Mt CO_2 removed assuming a 25 years lifespan
	Maintenance cost	The maintenance cost is mainly the cost including the production of lime (mining, grinding, calcination and hydration), the transportation and the transportation of the goods and the salary for the employees as mentioned in option 3.1.1. In total, the maintenance cost is 652.6~1261.3 M €.
	Monitoring, reporting and verification (MRV)	Monitoring networks in the North Sea is an international effort. The existing Ship-of-Opportunity, FerryBox-integrated, membrane-based sensor measurements complement the limited observational capacity of scientific research cruises and fixed-point observatories in oceanic regions. As stated in 3.3.1, on a large spatial scale the change of alkalinity is at least two magnitudes too small to detect, hence ocean models are an important asset for the long-term estimation of effectiveness.
Systemic parameters	max. CO_2 removal potential	31.28 Mt CO_2 removal per year, given the yearly production of limestone in Germany of 56Mt (BGR, 2021). However, it is possible to scale up the production as demand, given that the outcrop of pure carbonate is about 31 km^2 (Caserini et al., 2021).
	Permanence	in the form of bicarbonate in the seawater, expecting to be stable in the time scale of 100,000 years.
	MRV capability	Alkalinity, DIC and pH change can be measured, thus the carbon stock changes can be calculated. Fluxes can be estimated via modeling simulation. By combining the measured/calculated DIC stock changes and the modeling estimates of flux, the leakages can be subsequently calculated.

Table S3.1.2 Table describing the categories and parameters of the production and spread of Ca(OH)2 along ship tracks in the North Sea.

3.1.3 Coastal enhanced weathering (CEW) along the German coast

Area demand and potential:

The length of the German coast that is suitable for coastal enhanced weathering is 3,300 km. Assuming a width of 100 m and a depth of 10 m, the total volume is 3.3×10^9 m^3. Following Montserrat et al. 2017 (Figure 1), the increase of alkalinity (TA) after 5 days is maximized around 100 µmol/kg. For a volume 3.3×10^9 m^3 of seawater, the increase in TA is then 3.3×10^8 mol. For an assumed optimal case, each molar increase in TA results in one mole of CO_2 removal from the atmosphere. Therefore, 3.3×10^8 mol increase in TA is 3.3×10^8 mol, or 1.4×10^4 tonne of CO_2 removal. We assume a turnover of seawater in the German coast every 5 days, the amount of annual CO_2 removal is then $1.4\times10^4\times365/5$ tonne, which is 1.1 Mt CO_2 removal per year.

Material demand:
The material is assumed to be basalt, which is available domestically in Germany. For 1.1 Mt of CO_2 removal per year, the amount of basalt required is around 3 Mt per year (House et al 2007), which is about 10% of current German basalt production (BGR, 2021).

Energy demand:
The energy required for mining is 7.0 kWh/t (Foteinis et al., 2022, same as 3.1.1 and 3.1.3). The energy required for grinding to 10 µm is 173.71 kWh/t (Table 2, Hangx and Spiers, 2009). Hence the total energy for mining and grinding 3 Mt basalt is 542.13 GWh per year.

Water demand:
0.200 m^3/t mined (Foteinis et al,. 2022; same as 3.1.1). For 3 Mt basalt, 0.6 M ($0.2\times3\times10^6$) m^3 of water is needed. The difference in water consumption between grinding to 10 and 100 µm is unknown.

Cost estimate:
The cost is broken into (1) basalt mining and grinding, (2) transportation, and (3) MRV.

(1) For mining and grinding in €.

Basalt mining already exists in the region.The energy price from wind farming is 0.04 -0.08 €/kWh (Fraunhofer, 2021, https://www.ise.fraunhofer.de/en/publications/studies/cost-of-electricity.html; same as 3.1.1) hence for 72 GWh/ year, the cost is 2.9 - 5.8 (average 4.4) M € per year.

Grinding up the basalt rock to 10 µm needs about 542.13 GWh/year (see above), the cost is 21.7 - 43.3 M (averaged 32.5 M) € per year.

(2) Costs for transportation

The transportation costs consist of two parts. First part is to ship from the mining site to Emden (same as 3.1.1) and the second part consists of transportation by truck from Emden to coastal sites.

(i) Transportation of 3Mt of rock for 700 km by ships (cheapest solution in Germany) would be 0.0011 €/t/km ×3 Mt ×700 km= 2.3 M € per year.

(ii) For truck transportation cost, assuming the average distance is 500 km for 3 Mt basalt, then the cost would be 3 Mt *500 km* 0.08 = 120 M EUR (by truck 0.08 €/t/km)

(3) The cost of MRV is unknown (see 3.1.1).

Total cost: 4.4 +32.5 + 2.3 + 120 + MRV M € / 3 Mt = 159.2 million € / 3 Mt = 53.1 €/t

The cost breakdown for enhanced weathering includes basalt mining and grinding at around 36.9 million EUR, and transportation at roughly 120 million EUR. The total cost for these components amounts to approximately 160 million EUR. With a target of removing 1.1 Mt of CO_2, the cost per ton of CO_2 removal is approximately 53 EUR/t. It's important to note that these estimates are subject to variations based on specific project requirements, location, and market conditions, and do not include the cost of MRV.

Environmental Impact:
Enhanced weathering might pose an additional risk for coastal ecosystems and this might enhance coastal vulnerability to other stressors such as climate change, acidification and eutrophication. It poses risks to marine ecosystems and sensitive habitats like coral reefs (Doney, 2010; Kroeker et al., 2013). Also, there are concerns about health risks associated with finely crushed (1-10 um) material containing fibrous serpentine minerals like asbestos, as well as potential problems with wind-borne transport of fine ground olivine (Hangx & Spiers, 2009). Additionally, the biogeochemical interactions resulting from the introduction of olivine-rich rocks, rich in silicon, iron, nickel, and chromium, need to be considered. It is crucial to make sure that the amount of nickel and chromium introduced into the coastal environment by this option does not exceed the local marine environmental quality standards and impose any risk to local biota (Flipkens et al., 2021).

Category	**Parameter**	**Description**
Option description	Maturity level (Technology readiness level)	TRL5-6
	Infrastructure	Mining: mining site for basalt (same as option 3.1.1) Grinding: grinding machine/plants Transportation: distance is ca. 700 km freight transported by rail in Germany 2021: 123 Bt-km 17 Mt * 700 km = 11900 Mt-km = 11.9 Bt-km = 9.7% of the total capacity in 2021 (BMDV, 2016: https://bmdv.bund.de/SharedDocs/EN/Articles/WS/waterways-as-transport-routes.html).
	Biophysical conditions	Coastal region with high water turnover rate, so that the dissolved material can be effectively brought away from the site. In our option, we assume the turnover is within 5 days.

	Location	Mining: central Germany (site assumed the same as 3.1.1) Grinding: near the mining site Application: North Sea and Baltic Sea coast
Demand/Input	Area/land	330 km^2 coastal sea (total suitable coastal line is 3,300 km, here we assume that average depth is 10 m and the width of the water is 100 m) 312 m^2 for mining (according to Foteinis et al. 2022)
	Material/resources	Mafic and ultramafic rocks - Ultramafic intrusions (e.g., Norway, Germany) around 3 Mt per year (House et al. 2007), which is about 10% of current German basalt production (BGR, 2021)
	Energy demand	Mining: The energy required per ton of rock for mining is 7 kWh/ton (data from 3.1.1). For 3 Mt we need 7 kWh/ton * 3 Mt = 21 GWh Grinding: Grain size should be at the order of 10 µm (ch. 7 in NASEM, 2021, GESAMP, 2019) Grinding to 10 µm requires 173.71 kWh/ton (Beerling et al., 2020) Total energy needed = 173.71 kWh/t * 3 Mt = 521.13 GWh Transporting: The energy demand of cargo transportation with the railway is unknown in this case. But likely it can be assumed to be renewable-based.
	Water demand	600,000 m^3 fresh water for mining and grinding.
Output	CO_2 removal potential	1.1 Mt CO_2 removal per year
	By-products	unknown
	Energy output	No
Environmental parameters	Soils/sediment	Enriched nutrients and enhanced organic matter for sediment, which may lead to local oxygen deficient zones.
	Water	Fertilization of nutrients, change of pH, particle concentrations.
	Air	Dust is produced during grinding
	Noise	Mining and grinding produce noises.
	Ecosystem	Fertilization effects, and the change of pH and alkalinity.
Economic parameters	CO_2 removal costs	159.2 M €
	Investment intensity	Unknown.
	Maintenance cost	159.2 M €

	Monitoring, reporting and verification (MRV)	Similar to option 3.1.1.
Systemic parameters	max. CO_2 removal potential	1.1 Mt CO_2 per year
	Permanence	Dissolved inorganic carbon in the ocean, please use the numbers from 3.1.1
	MRV capability	Similar to option 3.1.1.

Table S3.1.3 Table describing the categories and parameters of the enhanced silicate weathering beach enrichment

3.1.4 Direct electrosynthesis of NaOH for OAE in desalination units in upwelling regions

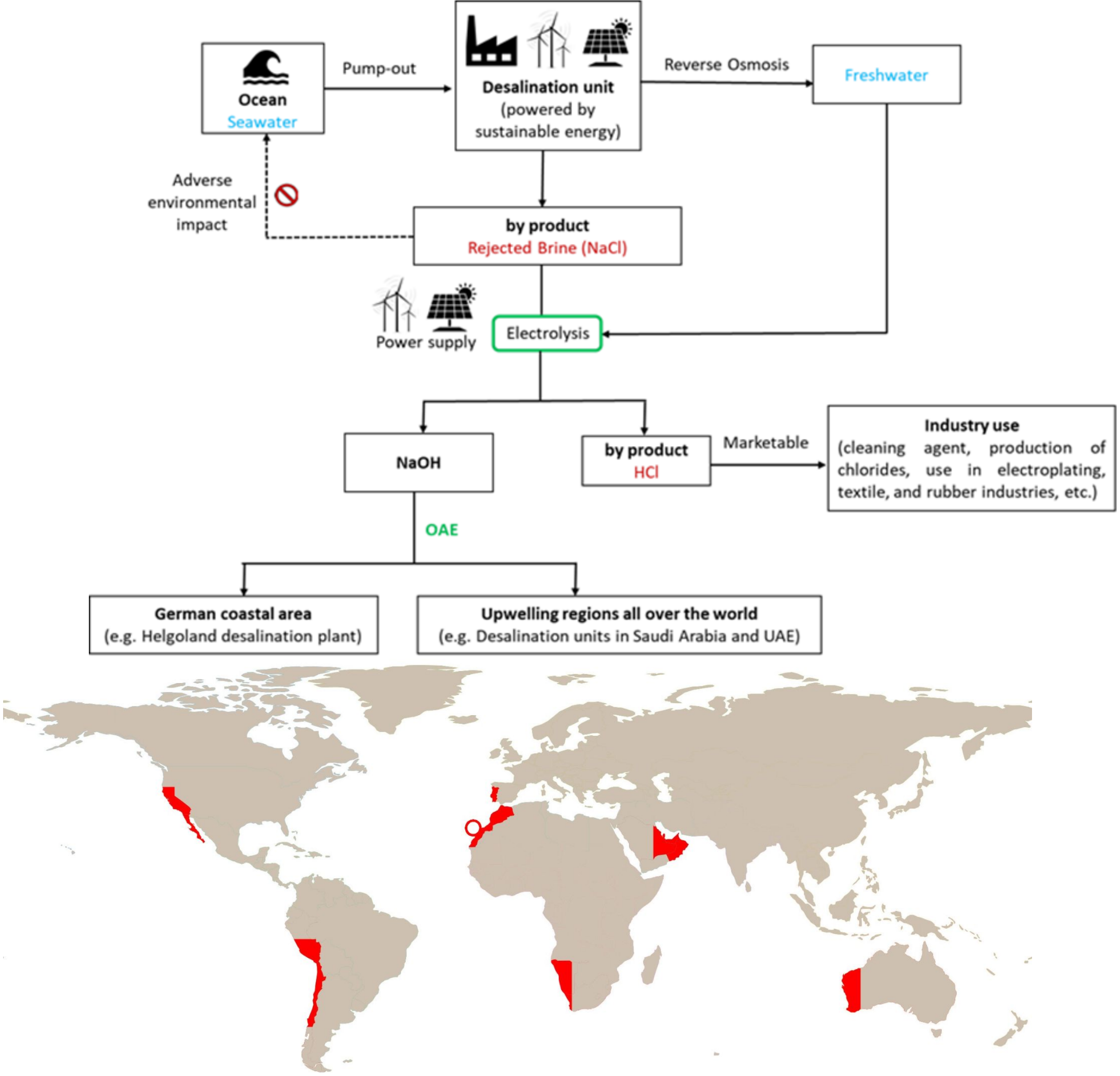

Figure S3.1.4 Block flow diagram for the production of high-alkalinity NaOH solution for alkalinity enhancement application (upper) and countries with upwelling regions (marked in red, bottom).

In many arid regions, desalination plants are the primary source of freshwater. During the desalination process, seawater is separated into freshwater and a brine. Due to the high salt content of the brine (NaCl), sodium hydroxide (NaOH) can be extracted via electrolysis and dispersed in the ocean to increase ocean alkalinity (Du et al., 2018). Currently, the United Arab Emirates (UAE) has 35% of the world's desalination capacity (Paleologos et al., 2018), which is used as a model location here. The UAE plans to invest approximately €1.86 billion in desalination plants by 2036 (UAE Desalination Plant Market report, 2023). Hence, the seawater processing capacity is not the limiting factor.

Description of the mMethod's cycle:

Brine solution is produced as a by-product of desalination plants, from which sodium oxide (NaOH) will be extracted via electrolysis process. The NaOH can be used as an alkaline solution to be dispersed on the desired site. The general method application cycle is as follow:

1. Retrieval of NaOH produced in the desalination unit
2. Production of high-alkaline solution
3. Storage of the alkaline solution for deployment
4. Monitoring of the in-situ biophysical conditions prior to deployment (MRV plan)
5. Transportation of the solution to the upwelling site
6. Deployment of the solution
7. Monitoring of the in-situ biophysical conditions during and post deployment (MRV plan)

As a note, a secondary by-product, hydrochloric acid (HCl), will be produced. This by-product could be sold to interested parties. For the purpose of this article, we are not exploring potential markets for the produced HCl.

Obtaining NaOH:

Considering a 1:1 mol ratio of NaOH used to CO_2 captured (Eq. 3.1.3a), then, theoretically, 10 Mt of CO_2 requires 227.3 G moles, which converts into 9.1 Mt of NaOH.

$$1NaOH + 1CO_2 \Leftrightarrow NaHCO_{3-} \qquad \text{(Eq. 3.1.3a)}$$

If 1 mol CO_2 equals 44 g, then 10 Mt of CO_2 equals ~ 2.2727 10^{11} moles. Therefore, theoretically, 2.2727 10^{11} moles of NaOH is equivalent to 9.0909 Mt (for a seawater with salinity of 35, where Na represents 10.78 g/kg).

Seawater demand:

The amount of seawater required to obtain ~9.1 Mt of NaOH will vary, depending on the salinity of the source water and the efficiency of the electrolysis membrane used in the desalination process. We estimate that for seawater with a salinity of 35 at 25 °C and a density of 1.025 kg/L, where a kilogram of seawater contains 11.1768 g Na^+ (Dickson & Et, 2007), $4.73*10^8$ m^3 of seawater is needed to achieve 10 Mt of CO_2 uptake. The northern Arabian Sea has higher levels of salinity (>35), which could lower the amount of seawater demand.

H_2 as a clean energy source for electrolysis:

During the desalination process, H_2 and Cl_2 are by-products (e.g., House et al., 2007), which could be sold independently as H_2 and Cl_2 gas. However, when using a fuel cell H_2 can be used as a clean energy source (e.g., House et al., 2007; Rau et al., 2013). Based on (Rau et al., 2018), the net energy demand for electrolysis could be reduced by 50% if considering the output of H_2 byproduct.

Annual capacity of one desalination plant (DEWA):

The DEWA Jebel Ali desalination plant in 2022 had a desalinated water production installed capacity of 2.2276 $*10^6$ m^3 per day and produced $6.2*10^8$ m^3 of fresh water (DEWA, 2022). Therefore, considering a 70% efficiency of the desalination plant (i.e., water recovery), it would be possible to obtain $2.7*10^8$ m^3 ($2.45*10^8$t) of brine solution with a density of 1.1t/m^3 in a year.

Then, using an extraction rate of 17.5 t of brine to 64.8 kg of NaOH (Du et al., 2018), a total of 1 Mt (dry weight) of NaOH would be produced annually by this desalination plant. This NaOH amount represents an annual potential to capture 1.1 Mt of CO_2 (see above 10 Mt CO_2= 9.1 Mt NaOH). We highlight that the desalinated water to brine conversion factor is a limitation, which depends on a myriad of factors, for instance the chosen membrane for electrolysis and presence of total dissolved material (Qasim et al., 2019).

<u>Deployment of the alkaline solution:</u>

The deployment method varies according to the site's hydrodynamics and biogeochemistry. We focused on areas where the desalination plant is in the coastal area. In this scenario, the deployment of the alkaline solution uses pipelines, thus eliminating expensive transportation costs using ships. The target areas are upper waters (within the mixed layer depth), preferentially at seasons with low biological activity and high mixing rates to not disturb the primary production activity and efficiently mix the NaOH-solution. Nonetheless, previous knowledge on the region and continuous monitoring of the field conditions are important.

Based on Hartmann et al., (2023) Experiment II results for OAE using NaOH solutions, the necessary sea surface area to deploy a similar NaOH-rich solution is estimated here. Since we suggest the release of the solution into the high-salinity surface waters (>35), we aimed at a TA addition of 300 µmol kg^{-1} (Experiment II) to a North Arabian Sea reference TA value (A_0) of 2300 µmol kg^{-1} (S=36, Anderson & Dyrssen, 1994) to reach a target TA (A_1) of 2600 µmol kg^{-1}. Hartmann et al. (2023) showed that 900 µmol kg^{-1} NaOH can be added into their model seawater, however, under the Arabian Sea scenario, we assume that an addition of 300 µmol kg^{-1} is safe from precipitation.

Therefore, adding 9.1 Mt (0.23 T mol, A_{added}) NaOH to seawater with a TA of 2300 µmol kg^{-1}, the minimal volume of seawater needed for the dissolution (V_{Needed}) would be 7.42 * 10^{11} m^3.

$$V_{Needed} = A_{added}/(A_1 - A_0) \quad \text{(Eq. 3.1.3b)}$$

It is crucial that the resulting solution do not exceed TA of 2600 µmol kg^{-1} to avoid precipitation. For summer conditions when the average mixed layer depth is 20 m (Anderson & Dyrssen, 1994), the necessary surface area is 3.71 x 10^4 km^2.

$$A_{Needed} = V_{Needed} \,/\, \text{mixed layer depth} \quad \text{(Eq. 3.1.3c)}$$

$$A_{Needed} = 7.42 \times 10^{11}\ m^3 /20m = 3.71 \times 10^{10}\ m^2 = 3.71 \times 10^4\ km^2 \quad \text{(Eq. 3.1.3d)}$$

In the case of the one desalination plant scenario (DEWA, 2022), which has a potential of removing 1.1 Mt CO_2 per year, the minimal volume is 8.1 $*10^{10}$ m^5, when released in summer at a seawater volume of 1000m^3. The total necessary surface area in summer for this scenario is 467 km^2.

MRV Monitoring system:

We considered low cost and maintenance as priorities for the design of the monitoring system. Therefore, we suggest mooring systems coupled with by-monthly cruises for discrete sampling. The moorings need to be equipped with a range of sensors that will provide information on the oceanographic and biogeochemical conditions as well as the primary production status. At least two moorings per site are recommended. A CDT is used to measure the temperature, salinity, and pressure. Other parameters like oxygen as oceanographic parameters; pH, CO_2, pCO_2, and NO_3^- as biogeochemical parameters; PAR (photosynthetically active radiation) and chlorophyll-*a* as proxies for primary production status should be monitored. All parameters should be measured at the top and bottom ends of each mooring. Specifically for the upwelling region, moorings should be placed at the top and middle of the continental slope as the upwelling cells vary in space coverage.

The maintenance and data collection of the sensors will be performed during the cruises for discrete sampling. Discrete samples of seawater need to be done close to the mooring areas for validation and verification and at one point in between the moorings. The water sample will be collected using a rosette-CTD cast. The sample water then will be used to estimate numerous parameters such as oxygen, pH, total alkalinity (TA), total dissolved inorganic carbon (TDIC), nutrients (total nitrogen and phosphate), and chlorophyll-*a*. All analyses should follow standard operating procedures (SOPs).

Energy cost calculation:

Worldwide the minimum energy consumption of desalination plants is 200 GWh per day, which is equivalent to 55% of the total managing costs of the plant, or 3-10 kWh to produce 1 cubic meter (https://theworld.org/stories).

The estimated energy demand for producing 1 kg of NaOH from rejected brine via electrolysis is 5.87 kWh (Du et al., 2018). For the removal of 10 Mt CO_2 the estimated demand of NaOH is 9.1 Mt, which translates into an energy demand of 53.4 TWh per year with the proposed method. Subtracting the H_2 production, assuming 50% of the energy is recovered by H_2 (Rau et al., 2018), results in a net energy demand of 42.7 TWh/yr. Additionally, the average US consumer cost is approximately € 0.61-1.23 per cubic meter of desalinated water (https://theworld.org/stories). Furthermore, the integration of renewable energy into desalination plants is estimated to grow by either implementing mixed energy sources or with 100% clean energy source (Du et al., 2018). In fact, a 100% clean energy desalination plant was reportedly successful in UAE for a 100 m^3 per day scale (Gordon, 2019).

Alternatively, the desalination and electrolysis units can also be run with bioenergy, hydropower, solar, wind, geothermal, wave energy etc. (Ghaffour et al., 2015; Gordon, 2019; Gude, 2016). Some desalination units are already running using solar (García-Rodríguez & Gómez-Camacho, 2001) and wind-power (ITA group, 2021).

Energy production is a limiting factor

In 2015, UAE generated 127 TWh (UAE Energy Report, 2015), but only 28+250 +17= 295 GWh =0.3 TWh is from solar.

Hence, if we want to achieve 10 Mt of CO_2 removal, we would need 42.7 TWh (see above), and we would have to use 142 times of the clean electricity available in 2015.

Hence the capacity of CO_2 removal is limited by the renewable energy sector in UAE, which can achieve 6.4 kt per year in 2015.

However, according to IEA 2023 (https://www.iea.org/countries/united-arab-emirates) in 2020, UAE produced 137 TWh of electricity, of which 5.48 TWh is renewable (4 %). Hence, in 2020, UAE can achieve (if using all renewable) 1.3 Mt CO_2 /yr.

According to (UAE embassy, 2023), UAE's goal is 30% clean energy in their energy mix in 2030 and 44% in the mix in 2050.

It would be possible to reach 10 Mt CO_2 /yr scale in UAE in the future.

Additional cost estimations

Costs associated with the desalination unit:

- Collecting and storing the residual brine

Costs associated with transportation of the NaOH solution:

- Using a pipeline: The desalination plants already use pipelines to return the brine solutions to the sea, which is potentially harmful for the local environment. By producing NaOH, the quantity of brine solution is either reduced or canceled. Therefore, the existing pipeline can be used to discharge the high-alkalinity solution for AE. However, further extension of the pipe connections may be necessary to reach the AE-target region, which costs would vary depending on the region.
- Using ships:
  - Container vessel: €140,000 - €150,000 per day (rental)
  - Material for deployment on the ship (not determined).

Besides, collection, storage, and dispersal of the NaOH will require additional costs. It can further vary based on the used dispersal method (i.e., pipeline and ships). Some other challenges are uncertainties in the cost estimates stemming from the efficiency of the electrolysis method based on used membranes, different energy prices in the respective countries, necessary investments for retrofitting desalination plants for renewable energy, and marketability of HCl or Cl_2 gas. In our calculations, we assumed that all sodium can be optimistically extracted from the seawater. In that aspect, larger quantities of seawater will be required.

Further considerations:

The effectiveness of OAE using high-NaOH solution will depend on the biogeochemical and hydrological condition of the waters. Therefore, a monitoring system is used to monitor the water conditions before, during, and after the release of the high-alkalinity solution. From displacing oceanic organisms to altering the surrounding salt concentration around them (https://theworld.org/stories), environmental impacts need to be closely monitored when OAE methods are applied. Less dissolved CO_2 due to higher alkalinity may reduce growth rates by calcifying organisms such as *Calcidisus leptoporus* and *Coccolithus pelagicus* (Langer et al., 2006). As the latter is an important primary producer, this may even lower the efficiency of net carbon removal and there may be a plateau of alkalinity addition regarding the efficiency of this method for carbon removal (Bach et al., 2019; Renforth & Henderson, 2017). Taking large volumes of seawater can harm and kill marine life like fish larvae (Missimer & Maliva, 2018). This could have environmental and economic impacts, as upwelling areas have large fishery economies. Another issue is the appropriate disposal of waste like HCl and higher concentrations of heavy metals that cannot be released into marine ecosystems without treatment. If the brine is released in the sea, the density needs to match that of the surface to promote further dilution (upwelling currents go out to sea), and not sink to the bottom where the high concentrations could kill the benthos. If the brine is disposed of on land, safe solutions for sediments, soil, groundwater, and humans need to be found. The acid needs to be disposed of in a safe way that does not produce harmful halogenated organic compounds (Kumar et al., 2019). Lastly, the method only functions for CDR if the HCl is not returned to the sea.

Environmental Impact:
This brine is contaminated with filter-cleaning products (anti-scalants and anti-foulants) from the desalination processes and enriched in heavy metals from the seawater, which impose potential danger to the local environment (e.g., Ahmed & Anwar, 2012; Al-Anzi et al., 2021; Jones et al. 2019). Another unknown factor is the possible impact of OAE on marine life (Albright et al., 2016; Bach et al., 2019; Cripps et al., 2013; Ferderer et al., 2022; Gately et al., 2023). As OAE increases the pH temporarily, it may impact the physiology of marine organisms and the ecosystem structure (Roberts et al., 2010). Additionally, the heavy metals' bioavailability might increase (Lattemann & Höpner, 2008). Therefore, it is essential to determine the biosafe limits of OAE and to regularly monitor seawater chemistry and its environmental impacts after the release of the alkaline solution.

Category	**Parameter**	**Description**
Option description	Maturity level (Technology readiness level)	TRL 3
	Infrastructure	Desalination plants at the coastal area; Ion-selective membrane to separate brine solution into acidic (HCl) and alkaline (NaOH) compounds; Energy and fresh water supplies. Pipeline to inject alkaline solution. Storage units for alkaline solution and HCl by-product.
	Biophysical conditions	German coast: low pH waters Upwelling: high TDIC (total dissolved inorganic carbon) concentration coupled with low chlorophyll-a and dissolved oxygen concentrations
	Location	Upwelling region: for example the Arabian Sea
Demand/Input	Area/land	No additional land required the construction of a desalination plant as this method plans on using the structure of existing ones. For the release of NaOH solution, it is estimated a total ocean surface of 467 km^2 based on experimental results of (Hartmann et al., 2023).
	Material/resources	Approximately 0.47 km^3 of seawater (at S=35) are required to daily extract 27 kt of NaOH to capture 10 Mt CO_2. For every 17.5 t/h of brine solution used for the electrolysis process, 208.4 kg/h of 32 wt % (64.8 kg/h, dry weight) of NaOH is produced (Du et al., 2018).

	Energy demand	Energy demand for the NaOH is 5.87 kWh/kg NaOH according to (Du et al., 2018) for a modeled system. 47.0-58.7 TWh per year for achieving 10 Mt CO_2 removal.
	Water demand	see Material/resources blow.
Output	CO_2 removal potential	1.3 Mt CO_2 per year
	By-products	HCl, Cl_2, H_2, and heavy metals depending on the chosen filtration and purification processes (Du et al., 2018). H_2 can be used as a clean energy source for the electrolysis process (e.g., House et al., (2007). Around 12 TWh of hydrogen per 10 Mt of CO_2.
	Energy output	Based on (House et al., 2007), H_2 energy production has a potential of reducing the energy demand of the electrolysis from 5.87 kWh/ kg NaOH to 4.7 kWh/ kg NaOH , when using the system proposed by Du et al., (2018).
Environmental impacts	Soils/sediment	To the best of our knowledge, not applicable.
	Water	Cl^- or HCl as a waste product; increase of alkalinity components (Mg^{2+} and Ca^{2+}) (Kumar et al., 2019) and pH may impact organisms' osmoregulation (e.g., (Roberts et al., 2010)
	Air	If the desalination plant runs on renewable energy, no air pollution.
	Noise	Not determined yet, but expected to be minimal.
	Ecosystem	Hardness might impact the osmoregulation of organisms (Roberts et al., 2010) and make heavy metals bioavailable (Lattemann & Höpner, 2008).
Economic parameters	CO_2 removal costs	€93/tCO_2 removed (EbbCarbon, 2024; Rau et al., 2013)
	Investment intensity	Ranging from approx. 0.2 to 0.3 €/kg NaOH depending on the evaporation system used (Du et al., 2018).
	Maintenance cost	Maintenance costs (short-term) are only significant for the monitoring mooring systems (cleaning of biofouling, exchange of sensors, data download, data management). Cost will vary depending on the ship used, estimated in 10s to 100s thousand €/day.
	Monitoring, reporting and verification (MRV)	Installation of mooring systems with oceanographic and biogeochemical sensors before the application of the method. Data management and sharing with local authorities (governmental and NGO) and the scientific community.
Systemic parameters	max. CO_2 removal potential	The lack of carbonate-system studies in the Arabian Sea prevents an accurate estimation. However, great potential is expected as the region is known for its production of pearls and coral reef tourism maintained by surface alkalinity drawdown due to precipitation.
	Permanence	This method prevents CO_2 outgassing when bottom water reaches the surface at upwelling sites. DIC would form bicarbonates that have a potential storage of ~10 000 years.
	MRV capability	Direct measurement of NaOH at the desalination plant. The monitoring of biogeochemical parameters provide the tools to calculate buffering capacity and estimate the rate of carbon storage.

Table S3.1.4 Table describing the categories and parameters for the direct electrosynthesis of NaOH for OAE in desalination units in upwelling regions

3.2 Blue Carbon Enhancement - mCDR options increasing carbon capture and sequestration by marine ecosystems

Here we provide schematic drawings (Figure S3.2.4), tables of categories and parameters (Table S3.2.1- S3.2.4) and extended explanation of the estimates for the four blue carbon enhancement options described in this study.

3.2.1 Introduction of kelp forests in the coastal waters of Heligoland

The most recent estimation of kelp productivity is 340 (166-738) g C m^{-2} yr^{-1}(Smale et al. 2020). This amounts to 1247 g CO_2 m^{-2} yr^{-1}. To reach the goal of 10 Mt CO_2 a total area of about 8000 km^2 would be needed.
Within the depth range of 1 to 13 m, there is around 24 km^2 of coastal area around Heligoland (BSH, 2018). Around 11 km^2 is already occupied by kelp (Schubert et al., 2016), leaving around 13 km^2 for potential extension of the kelp forest. With 13 km^2 available, we estimate an annual sequestration potential of 16 211 t CO_2 according to the kelp's carbon binding capacity (Smale et al. 2020).

The estimated cost per m^2 utilizing the green gravel approach is 6.75 USD (Fredriksen et al., 2020), which translates to 6.27 EUR using the exchange rate of 1 USD = 0.93 EUR. To plant 1 km^2 of kelp forest would therefore cost about 6 227 500 EUR. To reach the 10 Mt CO_2 goal and plant 8 000 km^2 of kelp forest would cost a total of about 50 220 000 000 EUR.

116 kg of gravel were used to produce enough green gravel for an area of 314 m^2 (Fredriksen et al., 2020). For the 8 000 km^2 to reach the goal, a total of 3 000 000 t of gravel would be needed. For Heligoland (13 km^2) a total of 4810 t would be needed.

The energy required is limited to the growing phase and deployment. For this option the kelp will be grown in a laboratory facility. Since no previous kelp cultivation studies or pilot projects were carried out at this scale, we considered an energy consumption range for the growing phase from high and low energy intensity greenhouse use in EU (250 - 12 000 Gj/ha; 0.007 - 0.33 MWh/m^2) (Paris et al. 2022). Considering that 15 kg gravel would occupy about 1 m^2 (about 1 cm grain, density 1.5 t/m^3), we would need about 320 m^2 per year in order to produce 4810 t. Since green gravel can be grown in cycles in the same lab, and it takes 70 days per cycle, this reduces the required area per year to 64 m^2. Given the energy demand from green houses in Europe between 0.007-0.33 MWh/m^2, the annual energy demand for a plantation in Heligoland would be 0.4-21 MWh. For a 8000 km^2-scale operation, the 0.2- 12.9 GWh yr^{-1}.

Calculations:

- Area needed:
  - Productivity of kelp: 340 (166-738) g C m^{-2} yr^{-1}
  - C in CO$_2$: 340 g C m^{-2} yr^{-1} x 3.67 = 1247 g CO$_2$ m^{-2} yr^{-1}
  - 10 Mt CO$_2$: 8 000 km^2 (potential area outside the German Bight)
  - 13 km^2 (Heligoland potential area): 0.016 Mt CO$_2$ yr^{-1}
- Costs for 8 000 km^2 kelp forest
  - The conversion between dollar and Euro uses the exchange rate in 2023 (1 $ = 0.93 €).
  - 6.75 USD per m^2 of planted kelp forest with green gravel approach -> 6.27 EUR per m^2
  - 1 km^2 = 6 227 500 EUR
  - 8 000 km^2 = 50 220 000 000 EUR
  - 13 km^2 = 80 957 500 EUR
- Green gravel needed:
  - 116 kg for 314m^2 restored kelp forest
  - 8 000 km2 = 3 000 000 t
  - 13 km^2= 4810 t

Category	**Parameter**	**Description**
Option description	Maturity level (Technology readiness level)	8-9 All steps of the green gravel approach (spore/seed collection, cultivation, deployment) are known and already in use.
	Infrastructure	For the production of the seedlings a cultivation facility is needed. This facility, depending on the site, can be mobile or on land. Mobile hatcheries are in development. For the collection of fertile kelp material divers are needed. For the deployment a boat is needed.
	Biophysical conditions	The limiting environmental parameters for kelp afforestation along the European Atlantic coast is the substrate. Kelp needs a solid, rocky surface to attach to. Another important factor is light as kelp is a photosynthesizing

		organism. Depending on the turbidity of the water kelp can grow up to 40 m depth.
	Location	Heligoland in the German Bight for the kelp forest and a cultivation facility; other sites along the European Atlantic coast; Gravel will come from quarries near Hannover (currently 227 Mt per year in Germany).
Demand/Input	Area/land	13 km^2 (Heligoland potential area); 8 000 km^2 for 10 mt CO$_2$ removal
	Material/resources	In case of existing local kelp populations, fertile kelp needs to be collected to obtain spores. If no local populations are present, suitable material needs to be selected. Gravel is brought from Hanover and transported to Heligoland via Bremen/Bremerhaven for the seedlings to grow on. For 8000 km^2 about 3 000 000 t is needed. For 13 km^2 in Heligoland about 4.8 kt is needed.
	Energy demand	The demand for energy would only exist in the phase of cultivation for the facility and during deployment for the boat (the latter may be considered irrelevant as the distance traveled for the deployment is close to the coast). The energy requirement for the cultivation ranges between 0.003 to 0.16 Twh per year, depending whether low or high intensity energy intensity is considered (Paris et al. 2022), which are 0.4-21 MWh yr^{-1}, for the 0.016 Mt CO$_2$ scale and 0.2- 12.9 GWh yr^{-1} for the 10 Mt CO$_2$ scale respectively. The only recurring annual energy demands would be those for monitoring and potential replanting of kelp.
	Water demand	Seawater is only needed during the cultivation of the kelp. This water can be pumped directly from the ocean into the cultivation facility. Most coastal research facilities have direct access to seawater, therefore, no transport of water is needed.
Output	CO$_2$ removal potential	16 211 t CO$_2$ per year at Heligoland, 0.00124 Mt CO$_2$ km^{-2} yr^{-1} at other sites.
	By-products	Kelp biomass can be utilized in many different ways (e.g., food, energy, fertilizer, extraction of compounds, etc.)
	Energy output	not relevant in this setup.
Environmental impacts	Soils/sediment	None
	Water	None
	Air	None
	Noise	Some noise during the preparation of the ground. No significant noise increase against the background shipping routes nearby for the monitoring.
	Ecosystem	If a new kelp forest is established, the species composition of both plants and animals of that area could change.
Economic parameters	CO$_2$ removal costs	Not applicable; once kelp forest is planted only monitoring and maintenance is needed.
	Investment intensity	50 billion EUR (for 10Mt CO$_2$ removal)

	Maintenance cost	After deployment only monitoring and optional replanting will be needed. Costs depend on the scale of the afforestation area.
	Monitoring, reporting and verification (MRV)	Existing monitoring programs need to be continued and in case of afforestation additional monitoring programs need to be established.
Systemic parameters	max. CO_2 removal potential	At Heligoland, it is 16 211 t CO_2 per year. While huge uncertainties for german-wide and global scaling.
	Permanence	We expect the kelp to be transported to the deep sea where the CO_2 is stored for centuries. For the kelp that gets washed ashore it depends on the utilization. If it is left at the beach, it will decompose and the CO_2 will be released back into the atmosphere.
	MRV capability	Currently, methods for exact calculations of CO_2 transport and storage are under development.

Table S3.2.1 Table describing the categories and parameters of the introduction of kelp forests in the coastal waters of Heligoland

3.2.2 Mangrove (re)establishment in Indonesia

CO_2 removal:
To calculate the area necessary for the removal of 10Mt CO_2 per year by mangroves, we considered the carbon sequestration rate of the restored mangrove forests in Bali, Indonesia, which is 10.6 ± 0.9 Mg C ha^{-1} y^{-1} (Cameron et al. 2019) Then the area to reach 10 Mt per year would be 9,434 km^2 (10 Mt / 1060 Mg km^{-2} yr^{-1}).

According to Sasmito et al. 2023, 193,367 ha, or 1,933 km^2, are suitable for mangrove (re)establishment. (Re)establishing these areas would remove: 193,367 ha * 10.6 Mg CO_2 ha^{-1} yr^{-1} = 2 Mt CO_2 yr^{-1}.
Mangroves can store not only CO_2 but also other greenhouse gasses (GHGs) such as N_2O and CH_4. If we take the carbon sequestration rate of mangroves in Tiwoho 27.6 ± 1.7 Mg CO_2-equivalent ha^{-1} yr^{-1} (Cameron et al. 2019), then the area to reach 10 Mt per year would be 3,623 km^2 (10Mt / 2,760 Mg CO_2-equivalent km^{-2} yr^{-1}). If we take the estimation of a total highly restorable mangrove area in Indonesia, the carbon dioxide removal by rehabilitating mangroves would be 5.33 Mt CO_2-equivalent per year (1,933 km^2 * 2760 Mg CO_2-equivalent km^{-2} yr^{-1}). Cameron et al. 2019 calculated the CO^2-equivalent as the difference between the GHG emissions of ecosystems present before the mangrove (re)establishment and CO_2 removals from (re)establishing mangroves.

Costs estimates:
According to the World Bank Briefing Note 2022, the cost of the mangrove restoration in Indonesia is 3,900 USD ha^{-1}, or 362,700 EUR km^{-2} (1 USD = 0.93 EUR), including 1 billion seeds per km^2 (Van Zanten et al., 2021). For the necessary area of 9,434 km^2, the total cost is about 3.4 billion EUR (9,434 km^2*362,700 EUR km^{-2}). One sack of propagules costs 0.66 EUR and consists of approximately 2,000 propagules (Chowdhury et al. 2018).

Thus, for one km^2 500 sacks are needed (1,000,000 / 2,000). Hence, the price of biomass to plant one km^2 would be 330 EUR. The total price of the biomass to reach 10Mt would be approximately 6 billion EUR (330 EUR km^{-2} *18,181 km^2). Transportation costs per sack are 0.32 EUR (given the plantation site is within 10 km radius of the nursery, Chowdhury et al. 2018). Thus, the total transportation cost to reach the 10 Mt challenge would be 3 million EUR (500 sacks / km^2 * 18,181 km^2 * 0.32 EUR).

Energy demand:
The energy demand for this option depends highly on the site (e.g., whether the ground is suitable for mangroves). When the ground is suitable, the energy cost would depend mostly on the transportation of propagules from the nurseries to the site, assuming that the cost for transportation above is only for the fuel. The cost of gasoline is 0.67 EUR per liter in 2019. Hence, 3 M EUR would be about 4.5 M liter gasoline, which would correspond to about 0.04 TWh energy (gasoline has 34.2 MJ/L energy).

Category	**Parameter**	**Description**
Option description	Maturity level (Technology readiness level)	TLR 9 (biological maturity level of photosynthesis)
	Infrastructure	Possible necessity of breakwaters and machinery for substrate replacement warehouses for the seeds and propagules storage.
	Biophysical conditions	- Tropical climate (or at least lots of sun and minimum moderate climate) - Propagules/seeds - Water (brackish to salty) - Substrate (mud or sand) - Suitable geomorphology: ● upper part of intertidal zone on the shores of deltas, estuaries, and lagoons ● open coasts sheltered from strong waves ● lee of headlands, islands, or reefs
	Location	Indonesia
Demand/Input	Area/land	9,400 km^2 (needed to fulfill 10 Mt of CO_2 removal)
	Material/resources	Suitable substrate (mud or sand but preferably from mangroves and not land substrate), and seeds or propagules depending on the species. Tools, and biodegradable material for hydrodynamic restoration/manipulation. Need little poly bags or pots.
	Energy demand	3 M EUR (transportation costs), interpreted to 0.04 TWh for 10 Mt CO_2 removal. - Driving between a warehouse and a planting field - Use of a boat if the replanting sites are not reachable by land If intense hydrological restoration is required, then some machines might be used to dig in the soil and create water channels, for example. However, no big power plants are needed.
	Water demand	Negligible: seawater or brackish/freshwater from the river in the planting area if there are seedlings that need to be watered. If propagules are planted directly in the field, then additional water is not needed at all.

Output	CO_2 removal potential	2 Mt (with the available 1,934 km^2 of land suitable for the mangroves reproduction); 10 Mt (9,400 km^2).
	By-products	Coastal protection, nursery grounds for commercial fish and crustaceans species, biodiversity increase, traditional medicine, dye, wood (small-scale construction/firewood), bioremediation, ecotourism, cultural and social values.
	Energy output	none
Environmental impacts	Soils/sediment	Erosion protection.
	Water	Clean up the water. There is some evidence to suggest that mangroves trap heavy metals (Castro et al., 2022; Kayalvizhi & Kathiresan, 2019) and can be used for soil remediation/waste water filtration (Theuerkauff et al., 2020). Furthermore, roots trap runoff sediment so seawater may become clearer. This is also beneficial for other ecosystems along the coastal gradient, like seagrasses and coral reefs, which need light.
	Air	Nitrous oxide, methane, and oxygen emission.
	Noise	Minimal noise since no heavy machinery is used.
	Ecosystem	Depending on which mangrove species we plant, microbiota might change, but no large negative impacts are expected. Positive impacts however should co-occur (e.g., increase of local biodiversity, coastal erosion protection).
Economic parameters	CO_2 removal costs	0.2 B EUR assuming a financing period of 30 years.
	Investment intensity	362,700 EUR km^{-2},and 3.4 billion EUR (to reach 10 Mt of CO_2 removal per year)
	Maintenance cost	Maintenance will probably only involve a few people regularly checking how the propagules are doing, so it would go hand in hand with monitoring and reporting. It is included in the costs above.
	Monitoring, reporting and verification (MRV)	The MRV is voluntary based, therefore the cost is null. However, depending on the scale of the project a specified entity (governamental, NGO) should act with unclear associated cost.
Systemic parameters	max. CO_2 removal potential	2 Mt per year in Indonesia
	Permanence	Solid form (living, dead) and dissolved & particulate biomass, as long as the forest is preserved
	MRV capability	Volunteers are needed to perform biomass and survival rate assessments once every two to three months, via sampling in different locations (sediment, water, air, biomass estimations).

Table S3.2.2 Table describing the categories and parameters of mangrove (re)establishment in Indonesia

3.2.3 Artificial upwelling to enhance plankton production and ocean CO_2 uptake in the North Atlantic

Assumptions, uncertainties and calculations:

Global AU modeling downscaled to regional AU (high uncertainty), without considering regional differences in the ocean or any impact on the land. C-uptake of the ocean ranges from 0.4 - 1 Gt C per year with 1000 meter long pipes, an upwelling intensity of 1cm/day (replaced at surface layer) and a pipe covered area of 250.000.000 km^2, if applied until the year 2050 (Jürchott et al., 2023). Downscaled pipe area to reach 10 Mt ocean CO_2 uptake is between 682,400 km^2 (from 1 Gt C / year) and 1,706,000 km^2 (from 0.4 Gt C / year).

Considering a pipe of volume equal to 6.28 m^3 (pipe dimension: 500 m length, 0.002 m wall thickness and 2 m of diameter), the energy necessary to produce it would be 1.3*10^5 kWh (energy demand of plastic production 20888,9 kWh/m^3). With a lifetime of the pipe of 5 years, the production energy demand per year would be 2.6* 10^4 kWh. Total production energy demand for 40 000 pipes = 1* 10^9 kWh = 3.6*10^6 GJ/10 Mt /year.
The total ship energy demand is 4.12* 10^8 kWh (1.5*10^6 GJ/ 10Mt /year). For a ship at 10 kn the energy demand is 5000 kW. The distance between the pipes is 10 nm. Considering the ship time per pipe is 1-2hr (adding 1h of operation at site may be short, but energy demand should be kept low, so continuing with 2h per pipe), the ship energy demand per pipe would be 1*10^4 kWh. To that, adding 12 eight-day voyages between site and land per year (for 10Mt) = 1.2*10^7 kWh.
The total energy demand for operation and installation would be thus 5.1*10^6 GJ/ 10Mt /year.

Costs for 1000m long pipes are unknown, but 500 m long pipe costs are assumed on the lower side with 60.000$ = 55.000€ per 250t CO_2 removed via one pipe (NAS, 2021). Upscaled to 10 Mt equals 2.200.000.000€ and an amount of 40.000 individual pipes (high uncertainty). If one pipe can last for 5 years, then the annual cost would be around 0.4 billion €. Costs do include production, shipping and ocean installation, but fail to include maintenance or MRV. Limited MRV may be done with remote sensing technologies, such as satellite imaging as well as ARGO floats and/or in-situ measurements / water samples and laboratory analysis.

Main restriction on AU is the permanence problem of the stored CO_2 (low uncertainty). Ocean circulation models suggest that, once AU is stopped, any additionally stored CO_2 will be released back into the atmosphere. The time frame of release depends on the location, depth and ocean circulation. The heat stored in the interior ocean via AU will radiate back into the atmosphere as well and will increase atmospheric temperatures above the reference level (reference level = future temperature, if no AU would have been done) (Oschlies et al., 2010; Keller et al., 2014). The positive effect on increasing primary production at the surface ocean may result in oxygen minimum zones below the surface ocean in the pipe covered area and an increase in the production of methane and nitrous oxide (N_2O). Both non-CO_2 GHGs if pumped up and released into the atmosphere may reduce or completely offset any atmospheric CO_2 reduction accomplishment via AU (Williamson et al., 2012; Palter et al., 2023).

Category	**Parameter**	**Description**

Option description	Maturity level (Technology readiness level)	TRL1
	Infrastructure	Fabrication, assembly, shipping, ocean operations, maintenance, MRV AUV's (e.g. ARGO floats) (NAS, 2021, p116). neary harbor(s) for operation.
	Biophysical conditions	High concentration of (preformed) nutrients at pipe source depth and low nutrient concentration at surface ocean.
	Location	North Atlantic subtropical gyre (oligotrophic surface water)
Demand/Input	Area/land	682.000 - 1.706.000 km^2
	Material/resources	Material to build 1000 m long pipes (plastic, steel) and bioavailable iron, if pumped up iron is not sufficient to sustain increased primary production.
	Energy demand	If wave-driven upwelling pipes are used, the upwelling process does not consume any external energy. The production of the pipes, which may have to be replaced regularly, is thus the main driver of energy consumption for this option (3.6*10^6 GJ/year). Ship operation for installation and maintenance of the pipes also contributes to the energy consumption (1.5*10^6 GJ/year). The total energy consumption for this option amounts to 5.1*10^6 GJ/year= 1.4 TWh/year.
	Water demand	Pipes would need to pump up enough water to replace a 1 cm thick layer per day in the pipe covered area.
Output	CO_2 removal potential	10 Mt / year of atmospheric CO_2 removal is reachable.
	By-products	Increased primary production (PP) may result in increased fish production, cooled surface air temperature and heated interior ocean in pipe covered area (lower global transfer efficiency rate -7.2%), potential formation of oxygen minimum zone, potential outgassing of methane and/or nitrous oxide (Dutreuil et al., 2009; Williamson et al., 2012; Oschlies et al., 2010; Keller et al., 2014; Jürchott et al., 2023).
	Energy output	none
Environmental impacts	Soils/sediment	none
	Water	Potentially pipe material released to the ocean (depending on the material used).
	Air	Potentially methane and/or nitrous oxides (N_2O) release (Dutreuil et al., 2009).
	Noise	none
	Ecosystem	Potential change from low nutrient adapted ecosystem to high nutrient adapted ecosystem (Ortiz et al., 2022)
Economic parameters	CO_2 removal costs	Unknown for 1000m long pipes. 55.000€ (60.000$) per 250t CO_2 for 500m long pipe with production, shipping, and ocean installation, but without maintenance, MRV (NAS, 2021, p116). For 10 Mt CO_2 removal per year, it will be 0.4 B EUR per year assuming the usage of the pipe is 5 years.

	Investment intensity	Unknown for 1000m long pipes. 55.000€ for one unit 500m pipes, 2.200.000.000€ for 10Mt CO_2.
	Maintenance cost	Costs (unknown) for pipe repair due to e.g. storm or bio-fouling damage.
	Monitoring, reporting and verification (MRV)	unknown
Systemic parameters	max. CO_2 removal potential	3.66 -7.32 Pg CO_2 / year (Keller et al., 2014; Jürchott et al., 2023).
	Permanence	Stored as DIC in the interior ocean ideally below pipe source depth. Storage duration varies from years to millennia depending on location, storage depth and general ocean circulation and stratification (Siegel et al., 2021). If pipe activity is stopped, any additionally stored CO_2 in the ocean will be released after years to decades back into the atmosphere (Oschlies et al., 2010; Keller et al., 2014).
	MRV capability	Low ability to confirm CO_2 removal. Problems include that PP and export production (EP) increase don't directly translate into increase of DIC at depth and DIC, as well as PP and EP move with currents and get diluted. Measurements for DIC at depth, pCO_2 at surface, (PP or EP not sufficient), and oxygen and temperature or possible food web changes.

Table S3.2.3 Table describing the categories and parameters of the artificial upwelling in the North Atlantic

3.2.4 Sargassum farming and sinking in the South Atlantic gyres

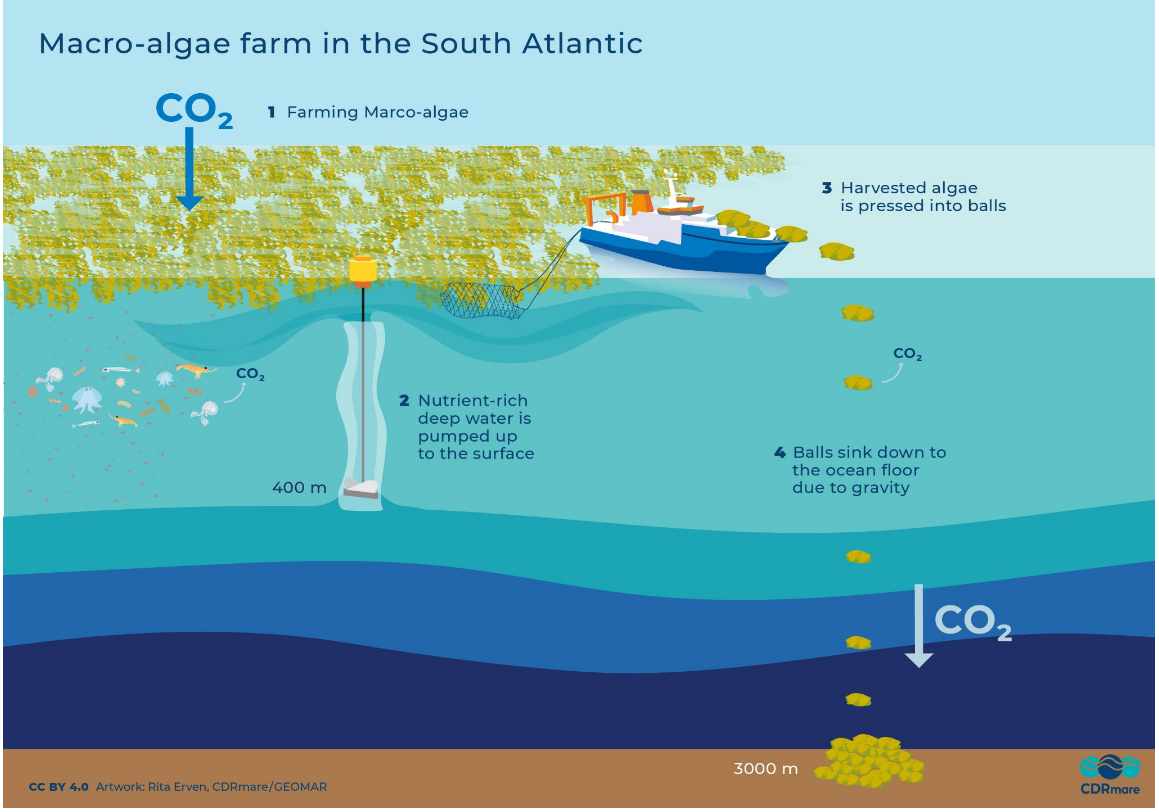

Figure S3.2.4 Schematic drawing for artificial upwelling with Sargassum farming and sinking.

The technological maturity level can be set to 2, as open ocean algae farming is currently at a conceptual stage. The logistical infrastructure, including workforce/human resources, needs to be established. Ideal conditions for Sargassum farming with artificial upwelling will be most likely in the South Atlantic gyre. The area needed was calculated based on the following parameters: the ratio of Sargassum wet-weight to dry weight was set to 5.9 (Carpenter et al., 1972), with a carbon content of 28% (Lapointe et al., 2021), and a C:N ratio of 32 and N:P of 12.5 (Lapointe et al., 2021). Sargassum growth rate per day was set to 0.034 (Howard and Mezies et al., 1969) with a density 3.5 kg/m^2 (Wang et al., 2018). The conversion factor from carbon to CO_2 is 3.664, so mass carbon is 2.73 Mt C, leading to 9.75 Mt dry weight of Sargassum needed to sequester 10 Mt of CO_2. This equals around 57.51 Mt Sargassum in wet weight based on the ww:dw ratio of 5.9. To maintain a constant standing stock of 4.63 Mt Sargassum, 0.16 Mt/day would need to be harvested, assuming that the harvested amount per day equals the amount of biomass that is grown per day. Calculated from the standing stock/wet weight of Sargassum per m^2, 1324 km^2 would be needed, equal to 3430 farms with 0.39 km^2 per farm. Yearly 57.51 Mt Sargassum would need to be harvested and sunk in bales to the deep sea.

In total, 740 million m^3 of deep ocean water per day with a nitrate concentration of 35 µM and a phosphate concentration of 2.2 µM (Garcia et al., 2013) would need to be upwelled. Therefore, 3430 farms with each 1 upwelling system with a flow rate of 2.5 m^3/s would need to be established for 10 Mt CO_2 removal/year. The raw value of deep ocean water (DOW) needed would be $2.03*10^{14}$ l, based on the calculation of the needed mol mass of nitrogen divided by the nitrate conc. of DOW/10^6. 75% of DOW was assumed to be used,

which equals a need of upwelling of 8577.87 m^3/s. One single pipe inside an upwelling pump can upwell water at a flow rate of 2.5 l/s, assuming reaching a flow rate of 2.5 m^3/s with an upwelling pump containing 1000 pipes. To sustain the necessary water flow, around 3430 pumps would be needed in total.
Each farm would need to be surrounded by one barrier and equipped with one boat containing the harvesting, shredding and baler system. The energy demand can only be estimated, but CDR efficiency would be highly dependent on the availability and feasibility to use electrically powered boats. The energy demand is mainly driven by the operation of the shredding and baling devices for Sargassum ($4*10^6$ GJ/year). Also, the maintenance of the offshore infrastructure ($2*10^6$ GJ/year) and the transport between the south atlantic subtropical gyre and the nearest land ($5*10^4$ GJ/year) are drivers for the energy demand of this option. The upwelling flow is generated by the salt fountain principle of Stommel et al. (1956) which does not require external energy input. The total energy demand for this option can be estimated to be $6*10^6$ GJ/year, which is 1.7 TWh per year.
The output of the farm reaches a CO_2 potential removal per year of 10 Mt. As by-products biofertilizer can be produced with 1.6 L water per kg of seaweed. In the total harvested biomass per year, 7.10 $*10^9$ mol nitrate per year can be gained. Applying a nutrient recovery of 25% from corn (Nagare et al., 2012) to Sargassum, 1.78 $*10^9$ mol N per year and $1.42*10^8$ mol P can be recovered. There is no energy output.

The costs of investment and maintenance of infrastructure plus man power and transportation accounts to 1060€ /tCO_2 removed. The TLR is still low, which increases the uncertainties of costs. The investment intensity was based on assumptions of costs of different offshore projects. The following costs were estimated for one farm: barrier (including skirt): 18.4 mill. € (based on ocean clean-up system), upwelling pipe system: 31.5 mill. € (Johnson & Decicco et al., 1983), collection boat: 790 000 € (Sargassum Hub). The costs for the shredding system cannot be stated as it does not exist yet. 10% of the total costs were added to cover additional needed infrastructure (5.1 mill. €), resulting in a total of 55.7 mill. € for one farm. To reach 10 Mt CO_2 capture per year, 3431 farms would be needed resulting in investment costs of 191.1 bill. €. To maintain the system, 3500 employees would be needed, costing 105 mill. € per year (based on aquaculture offshore farm, Buck et al. 2017). Transportation between farm and land was estimated to 24 travels per year for around 1200 nautical miles, resulting in 864.000 € fuel costs per year (based on aquaculture offshore farm, Buck et al., 2017). Autonomous collection boats and shredding devices are assumed to be powered by solar power. The yearly depreciation of the devices was set to 10%, assuming a running time of 20 years for all parts. The yearly reparation costs were set to 10% of the depreciation, resulting in reparation costs of 13.6 mill. €/year for boats, 541 mill. €/ year for pipes, 315 mill. €/year for barriers and 86.9 mill. €/year for the additional infrastructure. The reparation costs for the shredding devices cannot be stated. Summing up to 10.6 bill. €/year total costs (depreciation, maintenance, transport, workforce manpower).

Category	Parameter	Description

Option description	Maturity level (Technology readiness level)	TLR 2
	Infrastructure	3430 farms with each 1 upwelling system need to be established. Each farm needs to be surrounded by one farm barrier and equipped with one harvesting boat containing the screw press, baler system. Monitoring infrastructure and nearby harbor(s) for operation are needed.
	Biophysical conditions	Temperature, light, salt and wave conditions should be ideal in the South Atlantic for growing Sargassum. Nutrient will be added by upwelling nutrient-rich deep water from 400 m depths using the Stommel system (Stommel et al., 1956).
	Location	Farm located in the open ocean in the South Atlantic gyres, operation harbors in Brazil.
Demand/Input	Area/land	An area of 1,324 km² /10Mt /year is needed for this approach.
	Material/resources	Yearly 57.51 Mt Sargassum needs to be harvested and sunk in bales to the deep sea. 740 million m³ of deep ocean water per day with a nitrate concentration of 35 µM and a phosphate concentration of 2.2 µM (Garcia et al., 2013) need to be upwelled.
	Energy demand	Estimated energy demand is 4 $*10^6$ GJ/year for operation of the shredding and baling devices for Sargassum, 2 $*10^6$ GJ/year for the maintenance of the offshore infrastructure and 5 $*10^4$ GJ/year for the transport between the south atlantic subtropical gyre and the nearest land. The upwelling flow is generated by the salt fountain principle of Stommel et al. (1956), which does not require external energy input. The total energy demand amounts to 6 $*10^6$ GJ/year, which is 1.7 TWh per year.
	Water demand	The raw value of deep ocean water needed is 2.71 $* 10^{11}$ m³ per year. To sustain this water flow around 3430 upwelling pumps with a flow rate of 2.5 m³/s are needed.
Output	CO_2 removal potential	10Mt of CO_2 per year
	By-products	Biofertilizer
	Energy output	none
Environmental impacts	Soils/sediment	CO_2 might be released due to the slight microbial degradation of the surface of the bales.
	Water	The artificial upwelling releases nutrients in surface water, also micro-nutrients. Sargassum releases dissolved organic matter, from which the labile fraction is degraded by microbes and releases CO_2, whereas the refractory DOM is downwelled and enhances the amount of captured carbon (Buck-Wiese et al., 2023). The persistence of recalcitrant DOM is not included in the calculation.
	Air	none

	Noise	The harvesting of Sargassum and pressing of the bales cause noise.
	Ecosystem	Sargassum farming will probably attract various species, enrich the biological diversity (Casazza and Ross, 2008), increase albedo, lead to DOM production (Powers et al., 2019) and decrease the light ability at the surface. It might affect the microbial community in water and sediment, lead to potential oxygen depletion through biomass remineralization and potential methane and hydrogen sulfide production in the deep sea. Environmental impacts are still understudied.
Economic parameters	CO_2 removal costs	1060€ /tCO_2 removed
	Investment intensity	The TLR is not yet ready, which increases the uncertainties of costs. To reach 10 Mt CO_2 removal per year, investment costs of 191.1 bill. €. were calculated.
	Maintenance cost	10.6 bill. €/year maintenance costs.
	Monitoring, reporting and verification (MRV)	The daily-based monitoring will be simple. Initial cost for monitoring with drones is estimated to be 15 k€, assuming costs of 500€ per drone and the need of 30 drones to cover all 100 farms. Costs for in-situ nutrient analysis (nitrate+nitrite, phosphate) at 2 locations per farm are estimated to be approximately 30Mio € per year and for DOM it is unknown.
Systemic parameters	max. CO_2 removal potential	The max. CO_2 removal potential is huge, as one system needs an area of 1320 mill. m^2 in the subtropical gyre. Limiting factors are financial support and space.
	Permanence	Marine sediments in the South Atlantic serve as carbon reservoirs. The pressed biomass is expected to last around 1000 years. Additionally, recalcitrant DOM might form aggregates, which rain to the benthic floor, having as well a burial of around 1000 years (Powers et al., 2019; Buck-Wieses et al., 2023).
	MRV capability	Need to demonstrate carbon flow once initially. The size of the farms can be monitored by drones. Images can be used to calculate Sargassum biomass. The amount of biomass harvested and shredded can be weighed, as well as the amounts of bales sunk to the deep can be counted. Nutrient concentrations and amount of DOM fractions can be tracked in water columns.

Table S3.2.4 Table describing the categories and parameters of the artificial upwelling with Sargassum farming

3.3 Off-shore Geological Carbon Storage (offS) - mCDR options with technological carbon capture and subsequent storage in geological formations

Here we provide tables of categories and parameters (Table S3.3.1- S3.3.2) and extended explanation of the estimates for the two offs options described in this study.

3.3.1 Biomass from macroalgae farming for biomethane production combined with carbon storage in saline aquifers in the North Sea

General assumptions

Cultivating macroalgae offshore and utilizing the carbon-rich biomass as feedstock for biogas upgrading plants. The carbon captured by the macroalgae through photosynthesis will subsequently be sequestered following the production and upgrading of biogas, using Carbon Capture and Storage (CCS) technologies. The captured carbon will be stored in saline aquifers. The produced biomethane can be fed into the natural gas grid, used as a material in the chemical industry or used energetically (EBA, 2023).

Area/land

The limiting factor for area availability is the macroalgae cultivation. Both the area needed for biogas plants and the underground storage area available are negligible. CO_2 storage capacities largely exceed the available amount of CO_2, so this is not a limiting factor (Malischek and McCulloch, 2021).

Taking an averaged macroalgae yield of 20kg WW/m^2 (WW= wet weight, Buck and Buchholz, 2004b, Roesijadi et al., 2010), and considering the volatile solid (VS) content in macroalgae fresh biomass to be approximately 74% of WW (Roesijadi et al., 2010), the VS yield equates to 14.8 kg/m^2. To meet the biogas plants' demand for 10 Mt, it necessitates an annual VS input of 34.9*10^6 tVS/year. Consequently, for an upscale to 10 Mt, an estimated 2,358 km² of the German Exclusive Economic Zone (EEZ) would be required for offshore macroalgae cultivation.

The German North Sea EEZ area is 28,500 km², however the theoretical potential is lower due to competing uses as laid out in the National Maritime Spatial planning (BSH 2009). For example, the areas along the coast, shipping routes, nature reserves, etc. would have to be excluded. Cultivation in offshore wind farms is possible for reducing area demands (Buck et al., 2018).

Materials/resources:

Feedstock for one model biogas upgrading plant: 22.8 kt VS (volatile solids) year of macroalgae. This would amount to 34.8*10^6 t VS/year to reach 10 Mt removal. This was calculated using the following assumptions: an average biomethane potential of 210 mL

CH4/ g VS (Barbot et al. 2016), 8.7 * 10^6 m^3 raw biogas produced by one plant with a biomethane content of 55 %. No fertilizer is required.

Energy demand:

Energy demand is related to:

- macroalgae farming and harvesting (seeding/harvesting vessels, breeding labs),
- biogas upgrading plant operation: 0.210 kWh el/m^3 raw biogas (FNR 2019) which translates to 10.6 * 10^6 GJ per year to reach the 10 Mt
- CO_2 conditioning, transport, and storage.

The following assumptions are made: harvesting once a year, vessels fuelled by conventional fossil fuel (if implemented under current conditions), transport distance of macroalgae to coast: 200 km on average, biomass to be transported in order to reach the 10 Mt: 34.8 * 10^6 t VS/year. According to the number listed in Figure 9 in CESNI 2020, we assume that the push convoy for macroalgae harvesting consumes 13 liters of fuel per km for 7,500 t cargo.

Following the assumptions, the fuel required for macroalgae transport to reach the 10 Mt CO_2 goal is 33*10^6 L (for 12,699 vessels).

Notably, when combined with wind farms, the macroalgae farm maintenance and harvesting can share vessels with the wind farm (Buck et al., 2018).

Additional fuel required for CO_2 transportation assuming storage in saline aquifers close to the Norwegian coast. Following Jakobsen et al., 2017, 18*10^3 GJ/a fuel required per biogas plant; 27,8*10^6 GJ/a fuel required for 10 Mt CO_2 (61 biogas upgrading plants).

Energy demand for CO_2 conditioning, transport and storage (following Jakobsen et al., 2017) amounts to: 2.0*10^3 GJ/a (1 plant); 3.1*10^6 GJ/a (for 10 Mt) of electricity.

Water demand

Macroalgae: sea water demand of breeding tanks.

CO_2 capture process: the water demand is in the order of 0.5 to 1 m^3 per day per plant in the form of evaporation water (ISET/FNR 2008, https://www.infothek-biomasse.ch/images//2008_ISET-FNR_Biogasaufbereitung_Biomethan-Tagungsband.pdf).

CO_2 removal potential

Assumed 40 % CO_2 content in biogas (Hughes 2012; Lin 2019) and a 95 % separation rate: 6547 tCO_2 per plant per year. This value does not take into account lifecycle GHG emissions, it is only the capture “at the chimney”. For lifecycle GHG emissions from the model biogas upgrading plant, please consult Wollnik et al. (2023).

Costs

CO_2 removal cost is the cost estimate for a model BECCS biogas upgrading plant (gross costs, excluding revenues from electricity and fuels). The calculation is based on the investment and operating costs (excluding water scrubbing) and the CO_2 removal potential. The calculation is based on the avoided CO_2 cost methodology proposed by the Global CCS Institute (Kearns et al., 2021). The calculated value of 83 €/t CO_2 is within the literature range of 79 to 153 €/t CO_2 (Fuss et al. 2018).

Investment costs are related to macroalgae farming and biogas upgrading plant infrastructure.

Macroalgae farming: the price of a single offshore ring is 1,000 € but can be reduced and reused (Buck and Buchholz, 2004). The cost of initiating and maintaining the macroalgae farms are counted in the biomass price. Following the assumptions of Jakobsen et al. 2017, the investment cost for the CO_2 conditioning, transport, and storage is 264,000 €/a (values are annualized assuming a lifetime of 25 years) per plant.

Maintenance costs Macroalgae biomass price: highly uncertain in Europe due to scalability, location and the degree of mechanization readily achievable. Some examples: 3,870 €/ton FW in Norway 2020 (Directorate of Fishery, https://www.fiskeridir.no), 40 €/ton FW in France 2007 (Bruton 2009), 9,300 €/ton DW in Faroe Islands (~$100/ton DW in Asian countries (Gao et al., 2020). Following the assumptions of Jakobsen et al. 2017, the maintenance cost for the CO_2 conditioning, transport, and storage is 278,000 € per plant per year.

Additional explanation:

The experimental stage will involve species selection and evaluation of breeding and cultivation processes, with potential locations including Kiel, Bremerhaven, and Helgoland. For upscaled deployment, macroalgae plantlets will be bred in onshore facilities near the North Sea, such as in Bremerhaven, Cuxhaven, or Hamburg. After breeding, the plantlets will be planted on nearshore floating infrastructures like the offshore ring (Buck and Buchholz, 2004). These floating macroalgae farms will then be transported offshore and strategically located within the German EEZ (excluding natural protection areas and shipping channels), with the potential for integration with wind farms (Buck et al., 2018). Once the macroalgae biomass reaches maturity, it will be harvested and primarily transported to biogas upgrading plants located in northwestern Germany. However, the distribution network can be expanded to plants across the entirety of Germany, ensuring a sufficient CDR capacity (see Fig. 5-1 in Daniel-Gromke et al. 2018). Here, it will serve as a feedstock for biogas generation and upgrading to biomethane.

In Germany there are around 245 biogas upgrading plants (Daniel-Gromke et al. 2018). The model plant for the concept assumes a 2500 kW biogas upgrading plant. The CO_2 is captured pre-combustion by water scrubbing, a pressure-based process that separates biomethane and CO_2.

The Carbon Dioxide Storage Act (KSpG) implements the European CCS Directive, providing the legal framework for the pipeline-based transport and storage of CO_2. Currently (as of January 2024), according to KSpG §2, CO_2 storage sites in Germany are only allowed under three conditions: (i) the application must have been submitted until 2016, (ii) the storage capacity cannot exceed 1.3 million tons, and (iii) the total storage quantity cannot exceed 4 million tons.

Category	**Parameter**	**Description**
Option description	Maturity level (Technology readiness level)	● Feedstock: floating culture infrastructure: TRL 6 (field experiment - prototype in deployment environment, Buck and Buchholz, 2004; Buck et al., 2018; Fernand et al, 2017; Kim et al., 2017); ● Macroalgae aquaculture and harvesting: TRL 9 ● process: TRL 9: anaerobic digestion - fully commercial; biogas upgrading - fully commercial ● Product: TRL 9: biomethane ● CCS: TRL 8-9: full commercial scale demonstration ● Overall: 6, most process components are proven (exist in separated pilot or full-market applications), but have not been combined yet.
	Infrastructure	● Need for infrastructure for macroalgae farming: floating mariculture platform & harvesting/seeding machines and vessels (Buck and Buchholz, 2004; Buck et al., 2018). ● The technology uses already existing infrastructure for biogas production and upgrading. Depending on the plant location, different CO_2 transportation pathways are selected: road/railway transport, pipelines, shipping. For the 10 Mt scale-up, over 1500 plants would be needed. New large-scale biogas upgrading plants on the shore are an option to reduce transport demands.
	Biophysical conditions	Offshore, in the Exclusive Economic Zone (EEZ) of the North Sea where proper nutrients levels, temperature and current speed are provided for cultivation of macroalgae (e.g., *Saccharina latissima* (Weinberger 2020; Kerrison et al., 2015). Using macroalgae feedstock reduces the pressure on other biomass feedstock production (Kaltschmitt et al. 2016).
	Location	● Early-stage experiments: in the Kiel Fjord and/or at the North Sea coast line (e.g. Bremerhaven, Cuxhaven, Helgoland). ● Further deployment: coastal and open marine waters with proper nutrients & physical conditions in the German North Sea EEZ (~28,500 km²). ● Possible joint deployment with wind power plant farms (Buck and Buchholz, 2004; Buck et al., 2018). ● Biogas upgrading plants location (North of the shipping channel in the southern North Sea, close to the Netherlands).
Demand/Input	Area/land	Upscaled to 10 Mt: 2,358 km² (8.3%) of German EEZ area. There are available potential storage sites. From the GeoCapacity project, there are 262 sites in the German North Sea sector across five different geological formations, with a total capacity in the gigaton (Gt) scale (Vangkilde-Pedersen et al., 2009). Conceptually one storage site can be used for different mCDR options, however it would require additional surface and subsurface areas, + installation facility needs. For the deep subsurface area, the requirement is 10.204 m² per 1 Mt/year at a depth of 2.5 km (Borchers et al. 2022).
	Material/resources	Upscaled to 10 Mt: $34.9*10^6$ tVS/year. (VS= volatile solids)
	Energy demand	● Macroalgae farming and harvesting ○ 10 Mt: $40*10^6$ L (for 15,300 vessels) 1 liter of diesel has 10.6 Kwh, hence 0.4 Twh in total,

		possible emission is 2.68kg/L, hence 0.1Mt, which can be avoided when using electro-boats charged with renewables. ● biogas upgrading plant operation: ○ 10 Mt: $10.1*10^6$ GJ ● CO_2 separation, conditioning, transport, and storage ○ 10 Mt: fuel $27.8*10^6$ GJ; electricity $3.1*10^6$ GJ
	Water demand	● Macroalgae cultivation: Sea water demand of breeding tanks
Output	CO_2 removal potential	6.5 $ktCO_2$ per plant per year (Wollnik et al., 2023), hence over 1500 plants are needed for 10 Mt scale.
	By-products	Digestate which could be used as a fertilizer (Chen et al., 2015; Hughes 2012).
	Energy output	● 10 Mt: 7.3 $*10^9$ m^3 biomethane with an energy content of 263 $*$ 10^6 GJ ● 10 Mt: 5.7 $*$ 10^6 GJ externally usable heat (FNR, 2019)
Environmental impacs	Soils/sediment	No additional impact on soils.
	Water	Bioremediation of eutrophic water by assimilation and removal of nutrients (Phosphate and Nitrogen) (Marinho 2015)
	Air	Potential emission of HALO carbon (organohalogens-chlorides) from macroalgae could negatively impact ozone or UV flu. (Leedham 2013; Raven 2017; Jia et al., 2022; Tegtmeier 2012)
	Noise	Possible sources of noise: Harvesting and transportation of biomass; running of biogas plants. possible monitoring noise for the storage, see option 3.1.1
	Ecosystem	Ocean nutrients relocation / removal; reshaping of food web; potential increasing in mid-depth dissolved oxygen (Wu et al., 2023; Berger et al., 2023)
Economic parameters	CO2 removal costs	83 €/tCO_2
	Investment intensity	● Macroalgae farming: the price of a single offshore ring is 1,000€ but can be reduced and reused (Buck and Buchholz, 2004). ● Biogas upgrading plant (retrofitting) and CCS: ○ one plant: 264,000 €/a (values are annualized assuming a lifetime of 25 years) ○ 10 Mt: $403*10^6$ €/a (values are annualized assuming a lifetime of 25 years)
	Maintenance cost	● Macroalgae biomass price: highly uncertain ● Biogas upgrading plant and CCS: ○ one plant: 278,000 €/a ○ 10Mt: $424*10^6$ €/a
	Monitoring, reporting and verification (MRV)	Many of the developments in petroleum reservoir monitoring can be adapted and applied to CO_2 storage monitoring, especially the now widespread use of time-lapse seismic reservoir monitoring (Lumley, 2001), as demonstrated at

		the Sleipner project (Arts et al., 2004). The following monitoring options are available: time-lapse (4D) seismic monitoring, gravity field monitoring, surface gas monitoring and distributed fiber-optic sensing.
Systemic parameters	max. CO_2 removal potential	Can reach 10 Mt CO_2 removal
	Permanence	Assessment predicts that geological storage can retain at least 98 % of the stored CO_2 for 10,000 years. (Alcalde et al. 2018). We consider underground CO_2 storage in depths below 800 m which is assumed to be permanent. (Net Zero 2050 Team, 2021)
	MRV capability	The amount of CO_2 separated from the process is measurable on site. Storage sites are monitored using different techniques (acoustic, seismic, chemical, etc.), a detailed overview is given by Blomberg et al. 2021.

Table S3.3.1 Description of the biomass from macroalgae farming for biomethane production combined with carbon storage in saline aquifers in the North Sea

3.3.2 Off-shore carbon storage via mineral trapping in North East Atlantic basalts combined with direct air carbon capture

Calculations and further explanations:
To apply CO_2 capture from the atmosphere in combination with mineral trapping in offshore basaltic rock formations on a large scale, huge effort has to be made in building and improving DAC facilities, building infrastructure, and offshore injection sites.

Area/land to capture 10 Mt CO_2:
DAC requires < 0.001 ha (=0.00001 km^2) to remove 1 t CO_2 per year (Smith et al., 2016; Socolow et al., 2011).
Upscaling to 10 Mt: $0.00001\ km^2/tCO_2 * 10 * 10^6\ tCO_2 = 100\ km^2$

The area and the amount of material required to build DAC facilities to capture such large quantities of CO_2 are highly debated (Chatterjee & Huang, 2020; Realmonte et al., 2019, 2020).

Area/land to store 10 Mt CO_2:
10 Mt CO_2 in liquid state amount to 8.490 m^3 at the Earth's surface (based on: 1000 liter liquid CO_2 weighing 1178 kg), so a relatively small fraction of the 30.000 km^3 basalt in the Vøring plateau are needed.

This estimation, however, is only a simplification, since lateral and vertical variations of the geology occur, other minerals may precipitate in the pore space or CO_2 distributes anisotropically across the volume.

Water demand to capture 10 Mt CO_2 via DAC:
~700 Gt of water needed to capture 30 Gt CO_2/year (Realmonte et al., 2019)
Capture 1 Gt CO_2: 700 Gt water / 30 Gt CO_2 =~ 23 Gt water/Gt CO_2
Downscaling to 10 Mt: 0.23 Gt water = 230 Mt

→ ~230 Mt of water are required to capture 10 Mt CO_2

Water demand for CO_2 storage:
Not applicable in our scenario with injection of supercritical, liquid CO_2. Only needed if the CO_2 is dissolved in water for injection. Dissolution of CO_2 in water increases with pressure and decreases with temperature. At 25°C and pressures of 25-100 bar, 35-16 t of water are needed to dissolve 1 t of CO_2 (calculated with the geochemical modeling software *phreeqc* using the phreeqc.dat, Parkhurst et al, 1999; cf. Snæbjörnsdóttir et al, 2020).

CO_2 removal potential and energy demand of DAC plants supplied by energy of German North Sea wind parks:
High Temperature (HT-) as well as Low Temperature (LT-) DAC require around 1500 kWh of heat energy per t CO_2, and 300 kWh electric energy per t CO_2 (Borchers et al., 2020, Heß et al., 2020). In total, this amounts to 18 TWh of wind energy to solely capture 10 Mt CO2 from the atmosphere. In 2022, the North Sea wind parks generated 21.4 TWh of energy that was transferred to shore (TenneT, 2023). More than 6 MW of this was fed into the electricity grid.

The amount of CO_2 that could be captured by this energy amounts to: $21.4 * 10^{12}$ Wh / $1800 * 10^3$ Wh/tCO_2 = ~12 Mt CO_2

Using wind peaks to supply DACs with the required energy and heat, and considering the rapidly growing area of the North Sea wind parks in the near future (BSH, 2023), off-shore wind parks in the German North Sea could theoretically supply enough energy to capture 10 Mt of CO_2 by DAC technologies only. In addition, solar energy, energy-from-waste and waste-heat may be further options to operate DAC plants.

CO_2 transport by ships and energy demand for injection:
Cargo ships of different capacities (20,000 - 70,000 m^3 liquified CO_2) are or will soon be available on the market (e.g., by Wärtsila, https://www.wartsila.com/marine/products/gas-solutions/gas-carrier-solutions/liquified-co2-gas-carriers). The number of ships needed depends on several parameters, such as the transport capacity, the travel distance, and the discharge and injection rate.

Basic assumption:
Carrier S = 20000 m^3, offloading rate 1375 m^3/h, i.e. 14.5 h total
M = 40000 m^3

L = 70000 m^3, offloading rate 2750 m^3/h, i.e. 25.5 h total

Distance is 1800 km one way, i.e. 1000 nm, at 14 kn cruising speed this will be ca 72 hrs, i.e. 3 days.
Given the above offloading rates a round trip will be about one week total.
For 10 Mt CO_2 (= 8.490 m^3 liquid CO_2 we can calculate the following number of round trips:
S = 424, M = 212, L = 121
With three sites this will be ca 140x, 70x or 40x trips, which will require 8-10 small, 4 medium or 3 large carriers.
The required number of wells is variable and depends on the injection rate. Assuming an annual injection rate of ~1Mt CO_2/y (cf. Sleipner, Eiken et al., 2019), 10 injection wells would be needed. However, injection rates in basalts might be significantly higher due to their high permeability, reducing the number of wells or duration the infrastructure has to be rented. Therefore, for this scenario we assumed an injection rate which is higher than the rate at Sleipner. With an injection rate of 3.3Mt CO_2/year/well, 3 injection wells would be needed.

Liquefaction for ship transport:
Depending upon the composition of the CO_2-product stream, which depends on the DAC technology, the captured CO_2 has to be conditioned to meet the ISO 27913 with, e.g., a water content of <200 ppmv and a CO_2-concentration of >95%. The Climeworks technology reports CO_2-product streams with a CO_2 concentration of 99.9% (Viebahn et al., 2019), however, with other DAC technologies this value is significantly lower. For our calculations we *do not* consider CO_2 conditioning. If CO_2 conditioning is necessary, the energy amount is usually between 90-120 kWh/tCO_2 (Aspelund and Jordal, 2007), thus, for 10Mt of CO_2 this would amount to 0.9-1.2TWh.

Following the Climework technology, energy for cooling and compressing the CO_2 amounts to 0.113 MWh/t CO_2 and 0.038 MWh/t CO_2, respectively, with an inlet stream of 25°C and 1 bar. In total, this would need 1.51 TWh/10Mt CO_2 for liquefaction.

Conditioning for injection:
If the CO_2 is transported as cooled liquid (*e.g.*, -50°C, 7 bar), the CO_2 has to be heated for injection. Generally, this requires 0.112 MWh/t CO_2 of heat. However, the CO_2 can be heated and compressed to 10°C and 60 bar by seawater and waste heat recovery on board. Further heating and compression for injection: In case of direct compression without compressor at the bore hole to, *e.g.*, 300 bar, 0.0094 MWh/t CO_2 would be needed, resulting in 0.094 TWh/10Mt CO_2 (FICHTNER, see Supplementary Table "Technological Cost Estimation"). The pressure needed for injection depends on the depth of injection (hydrostatic pressure) and hydrological conditions in the reservoir. Depending upon the permeability and fluid flow velocities, pressure might be needed to displace pore water.

Category	**Parameter**	**Description**

Option description	Maturity level (Technology readiness level)	● Overall technology level Direct Air Capture and Storage (DACS) via mineral trapping: TRL 3-6 ● DAC: TRL 6 (currently operating on a small scale) (IEA, 2022). The largest DAC plant Orca in Iceland currently captures 4,000 t CO$_2$/year (Climeworks, https://climeworks.com/plant-orca). The Mammoth plant is currently under construction and will have a capacity of 39,000 t CO$_2$. ● CO$_2$ storage via mineral trapping: TRL 3-4. Small scale onshore projects exist. 1. Wallula Project (USA) injected around 977 Mt of CO$_2$ (McGrail et al., 2014) 2. The CarbFix Project in Iceland is injecting a mix of water, 12,000 tCO$_2$ per year (Snæbjörnsdóttir et al, 2020). Pilot projects on mineral trapping in offshore basaltic rock formations are currently running (CO$_2$SeaStone, SolidCarbon, AIMS[3], CO$_2$ Basalt, PERBAS).
	Infrastructure	● Infrastructure for DAC operation: Heat and electricity are provided by the German North Sea wind parks. Solar energy, energy-from-waste or waste heat may also be used. ● Use already existing North Sea wind park infrastructure with sea cables to the North East of Lower Saxony around Emden. ● CO$_2$ removed by other CDR options like BECCS can also be sequestered via mineral trapping. ● Long-term: Pipelines to transport high pressure gas/liquid CO$_2$ to storage site. ● Short-term: shipping (e.g., Reyes-Lúa et al., 2021) → storage hubs onshore and offshore FSUs (Floating Storage Units) are needed. ● Offshore wells: The injection rate critically depends on the permeability of the rock formation. Assuming annual injection rates between ~1Mt CO$_2$/y (rate at Sleipner; Furre et al., 2017) and ~3.3Mt CO$_2$/y, 3-10 injection wells would be needed for pure CO$_2$ injection, and a significantly larger number for dissolved CO$_2$ injection (at least 16x more). ● Floating production storage and offloading (FPSO) units/ turrets with risers
	Biophysical conditions	● Capture: Renewable energy to supply DAC plants ● Storage: Porous and permeable basaltic rocks, covered with low to impermeable sediment (thickness: 300+ meters)
	Location	● Storage site in the NE Atlantic at the NW European Continental Margin offshore Norway (Vøring Plateau): ~ 60,000 km^2 of basalt available, covered by impermeable sediment, lava sequences are at 1500 - 3000 m subsurface depth (Planke et al., 2021)
Demand/Input	Area/land	● Capture: DAC require < 0.001 ha to remove 1 t CO$_2$ per year (Smith et al., 2016; Socolow et al., 2011) → to remove 10 Mt, less than 100 km^2 are required ● 1 m^3 of young and fresh basalts can take up > 100 kg of CO$_2$ (Wiese et al., 2008). Assuming a storage capacity of 100 kg CO$_2$ per m^3 of basaltic rock, the volume required to store 10 Mt would be 0.1 km^3. ● The storage capacity of CO$_2$ in basaltic rocks at the NW European Continental Margin might be several Gt (Planke et al., 2021).
	Material/resources	● Sorbents to operate DAC plants (Realmonte et al., 2019, 2020; Chatterjee & Huang, 2020) ● Ammonia for CO$_2$ cooling cycles for liquefaction

	Energy demand	● High Temperature (HT-) as well as Low Temperature (LT-) DAC plants require both about 1500 kWh heat and 300 kWh electric power per t CO_2 (Borchers et al. 2022; Heß et al. 2020). According to these numbers, capturing10 Mt CO_2 would require 18 TWh energy in total. ● Additional energy is required for DAC material production (Chatterjee & Huang, 2020; Realmonte et al., 2020) ● Energy for liquefaction: Following the climeworks technology, this would need 1.51 TWh/10Mt CO_2 for a CO_2 inlet stream at 25°C and 1 bar (for cooling: 0.113 MWh/t CO_2, for compression: 0.038 MWh/t CO_2; FICHTNER, see Supplementary Table "Technological Cost Estimation"). Liquefaction technologies are discussed in literature and the energy demand is given to be ~1TWh/10MtCO_2 (e.g., Øi et al., 2016; Chen and Morosuk, 2021). ● Energy to transport the CO_2 by ship ● Energy needed to heat and compress CO_2 for injection: The CO_2 can be heated and compressed up to 10°C and 60 bar by using seawater and waste heat recovery on board. Further compression for injection: In case of direct compression without a compressor at the injection hole to, e.g., 300 bar, 0.0094MWh/t CO_2 would be needed, resulting in 0.094TWh/10Mt CO_2 (FICHTNER, see Supplementary Table "Technological Cost Estimation"). ● In Total: 19. 52 TWh /10 Mt CO_2
	Water demand	● Capture: ~700 Gt to capture 30 Gt CO_2/year (Realmonte et al., 2019) → ~230 Mt of water are required to capture 10 Mt CO_2 ● There are two pilot projects that plan to inject CO_2 into offshore basaltic rocks: CO_2SeaStone injects a CO_2-seawater mixture and the Solid Carbon project is going to inject supercritical CO_2. Both methods may be applied at the NW European Continental Margin, but they require different amounts of water and energy. ● If supercritical CO_2 alone is injected no additional water is needed ● If a CO_2 seawater mixture is injected the surrounding seawater can be used. CO_2 solubility in seawater is less than in freshwater (Weiss, 1974; Snæbjörnsdóttir et al, 2020). Depending upon pressure and temperature: if pressure is between 25-100 bar at 25°C, ~35-16 t of water are required to inject 1 t of CO_2 (calculated with the geochemical modeling software phreeqC, Parkhurst et al, 1999). To reach the 10 Mt goal ~160-350 Mt of seawater may be required.
Output	CO_2 removal potential	● Capture: In 2022, 21.4 TWh of wind energy generated in the German North Sea were transferred to shore (TenneT, https://tennet-drupal.s3.eu-central-1.amazonaws.com/default/2023-01/20230130_PM_TenneT-Offshore-Bilanz-2022_0.pdf). DAC plants require in total 1800 kWh energy (electricity and heat) per t CO_2 (Borchers et al., 2022). If the total amount of energy generated by the German North Sea windparks would be used, ~1112 Mt of CO_2 could be removed by DACs (assuming that wind energy is also converted to heat). However, offshore wind energy to operate DACs may especially be available during wind peaks which reduces the CO_2 removal potential. Still the amount of available off-shore wind energy is going to grow in the future (BSH, 2023). ● Storage: The storage potential of CO_2 in basaltic rocks at the NW European Continental Margin might be several Gt (Planke et al., 2021). Even if this capacity might be exhausted one day, large amounts of basaltic rocks (mid ocean ridge basalts, oceanic igneous

		plateaus or continental flood basalts) exist globally that may be feasible for mineral trapping of CO_2 (Snæbjörnsdóttir et al., 2020).
	By-products	● Carbonate and non-carbonate mineral formation during the reaction ● CO_2 emission during the construction of the infrastructure, CO_2 transport and injection
	Energy output	not relevant
Environmental impact	Soils/sediment	● Disturbance of sediments due to drilling
	Water	● There might be leakage of CO_2 into the water column, but it is expected to be low • In the reservoir: higher mobility of toxic metals (Matter et al., 2009). However, indications that they are immobilized with reaction progress (Flaathen et al., 2009).
	Air	not relevant.
	Noise	● Offshore wind power plants, drilling into basaltic rocks and pumping CO_2 into the rock formation ● Noise may be generated if active seismics are used to explore and monitor the reservoir
	Ecosystem	● Due to noise, drilling may destroy habitats ● Leakage events may have harmful effects on marine biota in the vicinity of a leaky well (Vielstädte et al., 2019) ● Basaltic rocks are porous and are also expected to be highly permeable on large scales, which makes them serve as aquifers for sea water. CO_2 storage via mineral trapping changes porosity and permeability of the basaltic rocks and hence, impacts the fluxes of seawater circulation through the basaltic rocks. This in turn may influence heat and chemical fluxes between the solid crust and the ocean. There is evidence that this circulation also occurs through basaltic rock formations of the NW European Continental Margin (Harris & Higgins, 2008)
Economic parameters	CO_2 removal costs	● Capture costs: span a wide range from 30-1000 USD/t CO_2 (Fuss et al., 2018, Keith et al., 2018) depending on the applied DAC system → scaling this up to capturing 10 Mt CO_2 would involve costs in the order of 100 M€ to 10 B€. More specifically, according to IEA (2022) for a large-scale plant built today, capturing CO_2 directly from the atmosphere would cost between 125 and 335 USD/tCO_2. Following estimates by (Fasihi et al., (2019), costs for low-temperature DAC of 10 Mt CO_2 would amount to ~1 to 3 B€. Generally, the costs are expected to fall in the future (Heß et al., 2020). ● Transport costs: We have calculated the transport distance from CO_2 originating in Germany to the Vøring plateau to be ~1800km. With a carrier vessel of large capacity (70.000m^3) and a round trip time of about a week (3 days one way at 14 knots) plus a day of offloading the CO_2 to an FSU (2750 m^3/hr), we would require 3 vessels at three boreholes for the duration of 12 months. With smaller carriers (20.000m^3 and half the offloading rate), the 10 Mt/yr would amount to 424 roundtrips and 8-10 vessels for 12 months. At a day rate of 20.000 - 30.000 €/day this would mean 58,4 to 87,6 Mill €.

		● In the literature, the costs for CO_2 storage are given to be ~20-30EUR/t CO_2. For further detailed information on transport costs for offshore storage see, e.g., ZEP, 2011; Roussanaly and Anantharaman, 2014. ● Costs of storing and pumping CO_2 into offshore basaltic rock formations are not well known yet, since the technology is still prototyped. Companies such as National Oilwell Varco (nov.com) have FSUs, carrier and Riser solutions at hand, but some of that may require specific construction of gear for such a project.
	Investment intensity	● Construction costs of the Orca plant that captures 4,000 t of CO_2 per year are said to be at 10 - 15 M USD (The Guardian, 2021, https://www.theguardian.com/environment/2021/sep/09/worlds-biggest-plant-to-turn-carbon-dioxide-into-rock-opens-in-iceland-orca (24.01.24)). Upscaling this to meet the 10 Mt goal seems unrealistic. We hence opt for a BECCS solution similar to that used in the North Sea sandstone project (see above). ● In an independent solution we planned with CO_2 carriers and an FSU at each of the three injection sites. While cost for the former has been calculated (see above), the latter remains largely unknown but will easily amount to 150 Mill € per site. Given the large network of pipelines in the North Sea and the Norwegian Sea to transport mainly natural gas already exists, some cost may be saved by using existing infrastructure for CO_2 transport (NPD, 2019). ● Environmental impact assessment needed at the injection sites ● Drill 3 injection wells down to 1000+ meters including casing/cement jobs and borehole completion for later injection. Cost strongly depends on the dayrate of the drilling vessel, with time estimates per hole ranging about 14 days. Plus mob/demob.
	Maintenance cost	Maintenance may not be required given that the CO_2 mixed with seawater is denser than SW and will stay in the underground.
	Monitoring, reporting and verification (MRV)	● Environmental monitoring around the injection sites with landers and occasional AUV (leakage from seafloor) and ROV (check borehole termination). ● Additional sensors: flow analyzer to investigate chemical composition of the injected gas, sensors ($p$$CO_2$, DIC, pH) to detect leakage, seismic monitoring (CarbFix, https://www.carbfix.com/proven (24.01.24))
Systemic parameters	max. CO_2 removal potential	This option realize negative emissions and remove several Gigatons of CO_2 from the atmosphere
	Permanence	● solid state due to mineral trapping ● long-term ● non-toxic ● water circulates a long time in the subseafloor, even if mineralization takes time, CO_2 can be trapped by solubility or residual trapping
	MRV capability	● monitoring by using lander equipped with proper sensors e.g., DIC ● geophysical monitoring ● observatories in monitoring wells ● Carbonatization: confirmed by drilling cores, fluid analyses, and isotope measurements

Table S3.3.2 Table describing the categories and parameters of the off-shore carbon storage via mineral trapping in North East Atlantic basalts combined with direct air carbon capture