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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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Abstract Marine carbon dioxide removal (mCDR) and geological carbon storage in the marine environment (mCS) promise to help mitigate global climate change alongside drastic emission reductions. However, the implementable potential of mCDR and mCS depends, apart from technology readiness, also on site-specific conditions. In this work, 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}, accounting 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 specific sites, within the German jurisdiction when possible. This serves as an entry point to discuss main uncertainty factors and research needs beyond technology readiness, and, where possible, cost estimates, expected environmental effects, and monitoring approaches. In total, we describe 10 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 10 options would potentially be implementable within German jurisdiction, and three of them could potentially meet the challenge. Our exercise serves as an example on how the creation of more tangible and site-specific CDR options can provide a basis for the assessment of socio-economic, ethical, political, and legal aspects for such implementations. The approach presented here can easily be applied to other regional or national CDR capacity considerations.

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

W. Yao and T. M. Morganti contributed equally to this work and share the first authorship.

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 help counterbalance projected future residual emissions
- Further site-specific studies are needed to assess the socio-economic, legal, political and ethical aspects of such implementations

Supporting Information:

Supporting Information may be found in the online version of this article.

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not only on technological readiness, but also on site-specific conditions. Our study explores the capacity of marine-based methods 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 CO_2 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 marine CDR (mCDR) and marine carbon storage (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 to 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, the CDR potential on land might be reduced, if current optimistic assumptions about land, fresh water, and energy requirements, as well as the development of storage capacities, are not met – possibly because their implementations would exceed environmental guardrails (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 mCDR categories: (a) the enhancement of the ocean's chemical carbon uptake through alkalinity addition, (b) the enhancement of the "blue carbon" sink capacity (such as in salt marshes, seaweed, or mangrove ecosystems), and (c) offshore 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

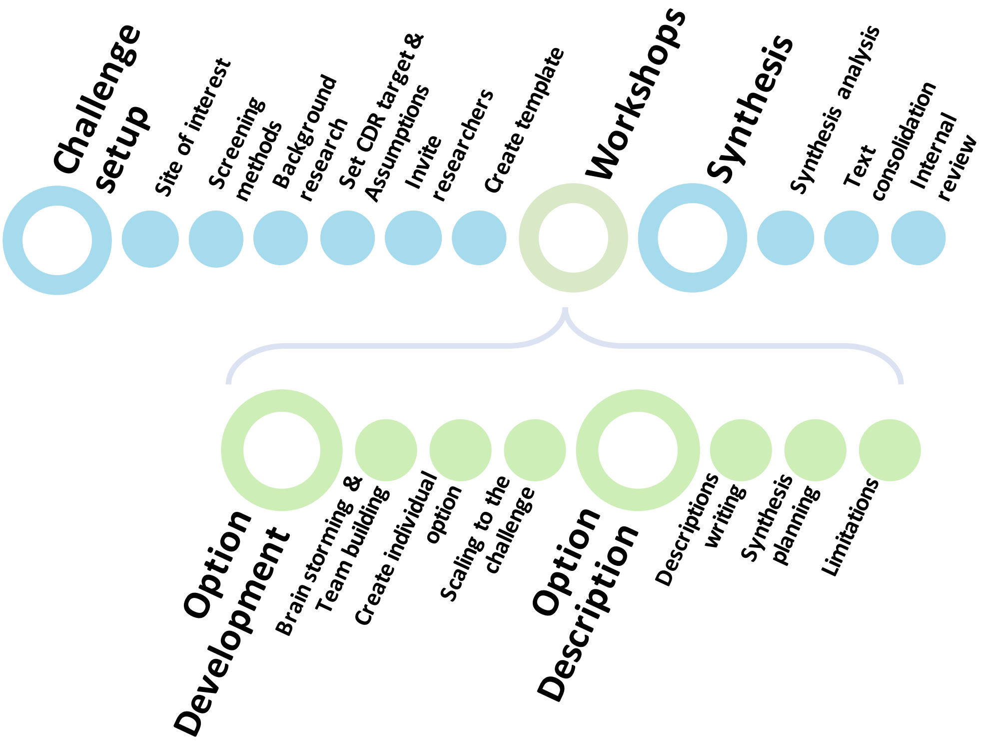

Figure 1. Roadmap for exploring site-specific carbon dioxide removal options with storage or sequestration in the marine environment pursued in this work.

of the aforementioned mCDR options at the same scale of operation. Our exercise does not aim to provide a comprehensive assessment of mCDR options or a dedicated life-cycle assessment, but rather to present a collection of options that can serve as a basis for further discussion, by making the scale of CDR implementation —relevant to national climate targets—more tangible. By doing so we aim to provide a basis for context-specific discussion and promote further studies that adopt a similar approach in other contexts worldwide.

To this end, we 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). For the case study, 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 efficiency and environmental effects. Ultimately, the approach we present here may serve as a template for exploring mCDR and mCS feasibility in further contexts worldwide.

2. Materials and Methods

This study aimed to develop site-specific CDR options through three phases: challenge setup, workshops, and synthesis (Figure 1). In the challenge setup, we identified the region of interest (Germany), compiled an initial list of CDR and carbon capture and storage (CCS) methodologies leveraging the knowledge in our research networks (CDRmare and CDRterra), and invited workshop participants. Background research included regional emissions, land/sea area, low-emission energy, material availability, and infrastructure capacity—factors influencing potential deployment (details are given in Section 2.2). These inputs informed our CDR scaling target and assumptions, defining criteria for significant contributions to reaching net-zero in our region of interest. We also designed a unified CDR options template (Table 1) to be employed during the workshop.

The second phase involved two workshops: the first focused on the creation and scaling of the options, generating over 13 options. The latter were screened resulting in merging similar options or excluding options due to

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 Supporting Information S1 Table S1)
	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 parameters	CO_2 removal costs	Marginal removal cost (assuming a fully established system)
	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

insufficient data. As a result, we generated a list of 10 CDR options, five of which could be implemented in the jurisdiction of the region of interest. The second workshop emphasized detailed option descriptions, discussed approach limitations (session 4.4), and planned the synthesis phase, including metrics for comparison and result formatting.

In the synthesis phase, we conducted comparative analyses (session 4.1–4.3) and an internal review within the research networks.

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 2A1). 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

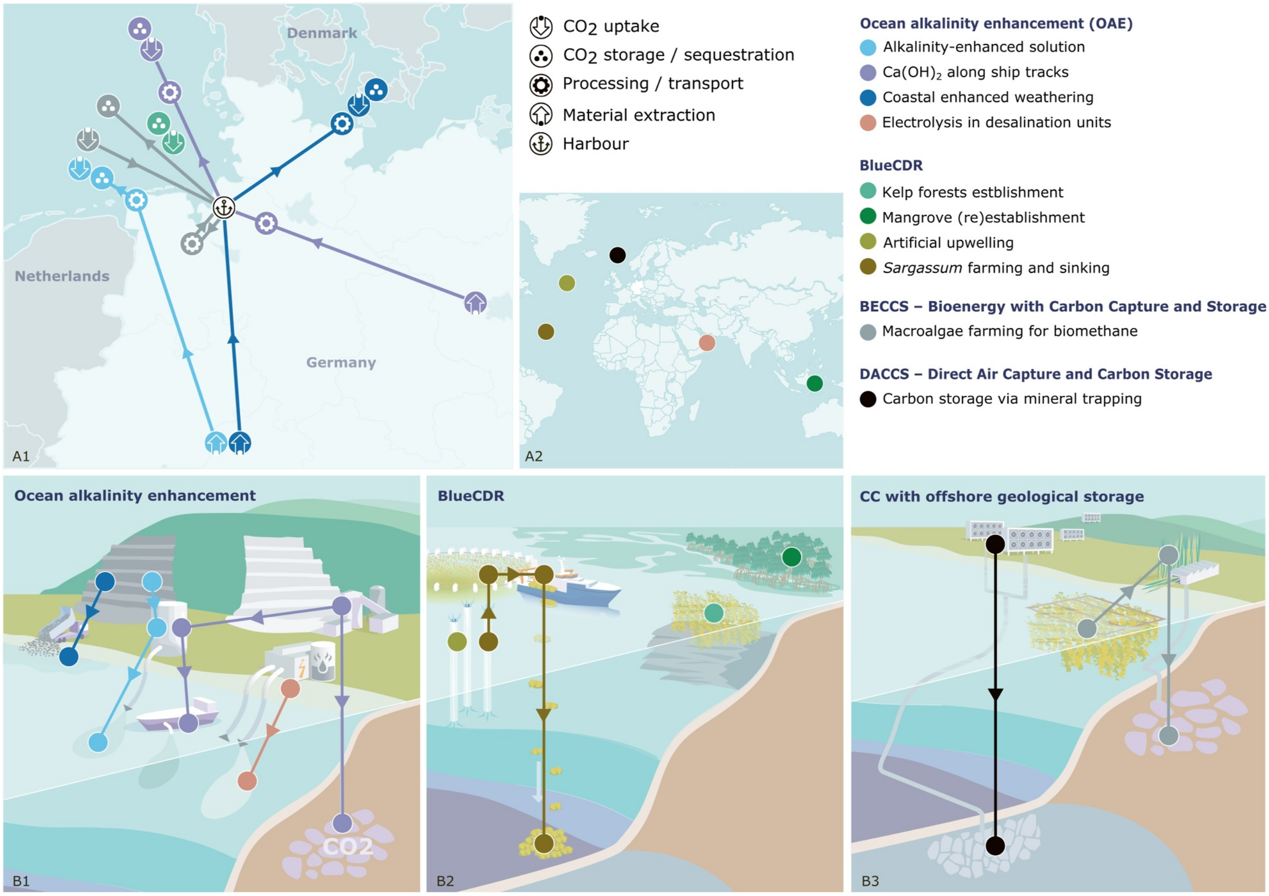

Figure 2. Schematic overview of the 10 mCDR options (clustered in three categories).

1. Map of Germany indicating the locations chosen for the implementation linked to the region where resources would be available;
2. World map for chosen implementation locations for international options (3.1.4, 3.2.2–3.2.4, 3.3.2).
3. (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, for example, material extraction, material processing, and implementation, while the arrows denote the movement of material down the chain. Note, for option coastal enhanced weathering, the deployment area is both in the North Sea and the Baltic Sea.

carbon storage (mCS) captured from the atmosphere, for example, 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 six of the Paris Agreement (UNFCCC, 2015).

This study describes necessary conditions for each option's implementation, including environmental conditions, infrastructure, 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.

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; Figure 1). 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 Supporting Information S1). Each option targets an annual removal of 10 Mt CO_2, with all demand, input, and output estimates calculated at this scale. The removal estimates and corresponding demands are derived from existing scientific literature, including laboratory observations, modeling works, method-based synthesis reports, and detailed life cycle analyses. 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; however, if the option reached 10 Mt CO_2 yr^{-1} removal, we asked for an estimate of the maximum annual CO_2 removal rate that could be achieved. 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) (Supporting Information S1 Table S1), assigned to each method is the lowest level depicted in the whole chain of technologies necessary for the respective mCDR implementation. The permanence, including the form of carbon sequestration, and expected length of storage was also detailed for each option, considering that permanent carbon storage after at least 1,000 years of storage (Brunner et al., 2024). Together with the fact sheets, schematic drawings of the options was developed (see Figures S1–S4 in Supporting Information S1) together with a summary figure (Figure 2). 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 10 options (displayed in 3 classes in Figure 2) 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 CO_2 yr^{-1} removal rate, the expected costs for such operations, and key uncertainties (for more details, please see Supporting Information S1). Discussions of the expected environmental effects, and challenges with regard to monitoring, reporting and verification for the options will be in Section 4.

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, 2020; Köhler et al., 2013; 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 2B1): 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 (sodium hydroxide, NaOH) seawater (see Supporting Information S1, 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 (Jones et al., 2014), the oceanographic conditions of the German North Sea characterized by shallow depth and high mixing rates (Sündermann & Pohlmann, 2011) would be very amenable to this approach. However, the actual efficiency of CO_2 uptake per unit of alkalinity added in the North Sea would need to be further investigated.

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 S1 in Supporting Information S1).

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; for calculations see Supporting Information S1 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; for calculations see Supporting Information S1 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 770–1,100 million € yr^{-1} for a 10 Mt CO_2 yr^{-1} removal rate including mining, transportation, energy, and investment costs without monitoring (for calculations see Supporting Information S1 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 and 600 μmol L^{-1} 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 (for calculation see Supporting Information S1 3.1.1) and additional in situ modeling studies 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 decarbonized 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 Slaked Lime 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 be transported to a harbor (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 German renewable electricity/energy production in 2021), 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 1,858 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 a 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 it might be possible with new lime plants (EuLA, 2014).

The total cost for 10 Mt CO_2 yr^{-1} removal is estimated at 800–1,450 million € with CCS applied for the lime production (calculation see Supporting Information S1 3.1.2).

One of the remaining challenges is the decarbonization 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-m-wide band, with an average depth less than 10 m along the beach; see Supporting Information S1 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 (TRL 8; "Vesta," 2022). However, the experiment aimed at demonstrating the efficiency of this method has yet to yield accessible results, so as of our study, the concept remains partially unproven. Hence by the time of our study, not all of the concepts are 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 (for calculation see Supporting Information S1 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} (for calculation see Supporting Information S1 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 million € (excluding MRV cost, for calculation see Supporting Information S1 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 (Ramasamy et al., 2024), 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 North Sea/Baltic Sea coastal ecosystems?

3.1.4. Direct Electrosynthesis of Sodium Hydroxide 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 brine. The retained salt in the brine can be split into sodium hydroxide (NaOH) and hydrochloric acid (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 reduce CO_2 emissions into the atmosphere by CO_2-rich upwelled water (Ali et al., 2021; Rau et al., 2013), 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 10 Mt 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 (DEWA, 2022). This option's 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^{-1} salinity to be processed by a desalination plant yearly (calculation in Supporting Information S1 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% and 90%). Upgrading such existing desalination plants to remove 10 Mt CO_2 would, however, require 42.7 TWh of additional energy per year (Supporting Information S1 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, the extraction of 10 Mt CO_2 is expected 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 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 produces 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 million € ("Ebb Carbon," 2024; Rau et al., 2018) to 3,850 million € (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, that is, 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 the 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 disadvantages 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). Permanent carbon storage is considered after at least 1,000 years of storage (Brunner et al., 2024). 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 2B2): option 3.2.1 focuses on the introduction 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 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 six 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 similar 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.

When the chosen reference baseline represents a time when the marine ecosystem was established and not degraded, the suggested (re)establishment approach is considered restoration. This restores degraded ecosystems to their baseline state, which avoids GHG emissions, but is not CDR (Mengis et al., 2023). However, if the reference baseline is the present—meaning the (re)established ecosystem is an "addition" carbon sink to the baseline—it qualifies as CDR.

3.2.1. Introduction of Kelp Forests in the Coastal Waters of Heligoland

The expansion of existing and introduction 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 planting 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 planting 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 (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 (for calculation see Supporting Information S1 3.2.1). The potential area for the introduction or expansion of kelp in Heligoland is around 13 km^2 (calculation see Supporting Information S1 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 planting.

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. This would be a one-time investment, with subsequent annual costs focused on monitoring carbon uptake and addressing potential replanting needs to maintain sequestration in case of disturbances. 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 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%–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 mangrove (re)establishment in Indonesia is explored. Indonesia is chosen as a case study since it currently hosts over 20% of the area of the world's mangrove 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 improve 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 seedling survivability (Hsiung et al., 2024). If necessary, hydrologic conditions might need to be restored to address stressors that have previously caused their declining numbers, by for example, 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 Supporting

Information S1 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 1,000 m length would be installed (see Supporting Information S1 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 1,000 m long pipes may be calculated from downscaled global modeling 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 around 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} without maintenance costs, see Supporting Information S1 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, Pahlow, et al., 2010; 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 Supporting Information S1 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, Pahlow, et al., 2010). 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, Pahlow, et al., 2010). Another considerable uncertainty within the development of this option is the durability and stability of the pipes once deployed. As of today, no existing pipe can operate at a depth of 500 m. Another challenge is the assessment of the localized impact that the increase of primary productivity induced by the upwelled water may have in the local food chain. So far, the impact has been studied only at the base of the food web (Ortiz et al., 2022; Tames-Espinosa et al., 2020) and additional experimental studies are required.

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 offshore 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} (for calculation see Supporting Information S1 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 that could 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 it 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 offshore storage of CO_2 (mCS) in combination with BECC or DACC. Note that geological storage of carbon emissions from fossil or mineral processes (here referred to as fossilCCS following Smith et al., 2023) is distinct from these mCDR approaches, since in this case the CO_2 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 liquefied 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 2B3): 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 DACC 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 the upper ocean crust is an interesting option for CO_2 storage, as basaltic rocks in general have the ability to react more rapidly with CO_2 to produce carbonates than sedimentary sandstones. The accelerated mineral trapping mechanism in basaltic reservoirs compared to conventional sandstone formations facilitates 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 and 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 EEZ (Buck et al., 2018). The macroalgae would be harvested once a year, and transported to biogas processing and 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 and 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 Supporting Information S1 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 (FMm^{-2}; 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 km^2 (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 Supporting Information S1 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 million 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 € per tonne of CO_2, which would amount to 830 million € 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 (megawatt scale) power 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, for example, 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 1,500–1503,000m (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/10 Mt CO_2, see Text S3.3.2 in Supporting Information S1) and stored in intermediate tanks. Assuming a distance of 1,800 km, three injection wells, and discharge rates between 1,375 and 2,750 m^3 hr^{-1}, transporting 10 Mt CO_2 yr^{-1} requires ~40 to 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 Supporting Information S1 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, for example, 300 bar, requires 0.094 TWh/10 Mt CO_2 (see Supporting Information S1 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 and highly uncertain (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 kt CO_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 and mCS options in this study covers different approaches for carbon removal technologies with sequestration or storage 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 offshore storage (mCS).

Within the generated mCDR option collection, six out of 10 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 2). 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-order 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 most of the mCDR options (e.g., 3.1.1, 3.1.2, 3.1.4, 3.2.3, 3.2.4, 3.3.2), except for the ecosystem-based options 3.2.1 and 3.2.2 with TRLs of 8–9 (Figure 3, Table 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 demand of harvesting and transporting 115 Mt of macroalgae biomass could potentially present another bottleneck in an at-scale implementation due to possible conflicts with other sea areas usage (e.g., wind parks). 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)

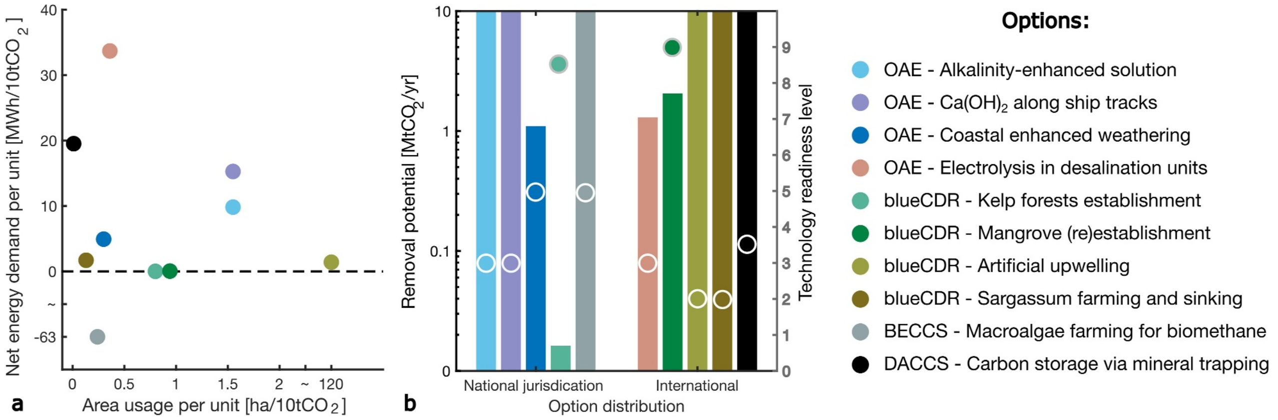

Figure 3. Summary and comparison of mCDR options at a scale of 10 tonnes of CO_2 removal. This figure shows net energy demand against area usage (a); and technology readiness level (white circles) against whether or not the option would be implementable in German jurisdiction and could reach a scale of 10 $MtCO_2$ yr^{-1} (b). The area usage displayed here includes estimated land and sea surface area. Net energy demand is given as demand minus supply, which can lead to negative values (produced energy). We chose to compare our options here on the basis of 10 tonnes rather than 10 megatonnes, to allow for a comparison at a scale that all the options could reach, and that would be significant to compensate for one person's annual emissions in Germany (8.7 t yr^{-1} for 2021).

and potential conflicts with other uses (e.g., marine protected areas, offshore wind, etc.) in more coastal areas (3.1.3, 3.2.1, 3.2.2, 3.3.1) remain (Table 2).

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 (Table 2).

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 indicated the research gaps and uncertainty related to possible environmental effects (Table 2) and we compiled here possible expected environmental effects gathered from the literature.

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 timescale, such an intervention could impact the physiology of marine organisms and the ecosystem structure (Roberts et al., 2010). If OAE options introduced 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, Koeve, et al., 2010). 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. In the case of upgrading existing desalination plants, the discharge from 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

Table 2
Overview of Bottlenecks and Research Gap/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	3.2.2 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 10 Mt CO_2 per year removal capacity										
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 other uses (e.g., marine protected areas)* For 3.1.4 there is possible conflict with space on land (safe storage of waste product HCl)				Possible conflict with other sea area usage* Area availability for creation of suitable substrate*	Possible conflict with other land or sea area usage*			High area demand and possible conflict with other uses (e.g., marine protected areas)*	Potential high 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*				Off-shore renewable energy (e.g., 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. Coastal erosion protection		Unknown		Unknown	
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 is unknown	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 commercial level			Upwelling pipe cost uncertain			No pilot projects exist, which makes 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)	Lack of permits to operate in international waters		Macroalgae productivity in the region	DACC capacity dependency

Note. "*"marks the current factor(s) restricting further upscaling of the option.

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 increase primary production and shift plankton community structure (Baumann et al., 2021; Ortiz et al., 2022). An increase of primary production results in an increase of carbon export and remineralization that could reduce oxygen concentration in 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, Pahlow, et al., 2010).

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 a subject for further studies.

The expected environmental impacts of offshore 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 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

The ultimate goal of CDR is to remove CO_2 from the atmosphere. Hence it is important to know how much of the carbon sequestered and stored would translate to reduction of the atmospheric carbon dioxide pool (Bach et al., 2023). The options in this study differ in permanence: while OAE and mCS options can last over 10,000 years, blueCDRs exhibit greater variability, ranging from centuries to millennia (see Tables S1–S12 in Supporting Information S1). 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, Petersen, et al., 2021). 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 potential 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, for example, DIC sensors, or isotope measurements of cores from monitoring wells to confirm the carbonization reaction.

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 (Tank et al., 2025; 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 three 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 an example on how to create context-specific CDR options for a more tangible and concrete basis for further studies and discussions. We believe that this format warrants application in many more contexts worldwide to address the global challenge of net-zero at an actionable level of detail. The resulting study is the first attempt at developing site-specific CDR options with storage or sequestration in the marine environment for a German context. 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 10 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 consider the GHG emission life-cycle, which is not ideal when it comes to the comparison of CDR effectiveness. However, due to the varying TRLs, many of these options cannot get robust emissions factors for life-cycle exercises, without further research. 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, leading to high uncertainty in our estimates. 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 GHG footprint 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 CO_2 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).

Data Availability Statement

This study did not involve the use of any datasets or computational models. The research is based on conceptual analysis and literature synthesis, with all sources explicitly cited in the main text of the article and the supplementary information.

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