WHITE PAPER

Harnessing The Ocean

How Closed System Marine Carbon Dioxide Removal (MCDR) Can Contribute to Meeting Global Decarbonization Goals

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Executive Summary

Durable carbon dioxide removal (CDR) is critical to meeting global decarbonization goals, particularly as emissions reductions alone could leave 6–10 Gtpa (gigatons per annum) of CO_2 unabated by the year 2050. In the near term, if companies proceed with meeting declared net zero targets by 2030, CDR demand could range from ~40–200 Mtpa (megatons per annum) CO_2 to as high as ~1.1–1.6 Gtpa CO_2. This contrasts sharply with an expected supply of just 15–32 Mtpa, requiring the adoption of all viable carbon removal pathways.

The recent agreement reached at the COP29 on Art. 6, promoting the establishment of a global carbon market, will play a significant role in advancing CDR development.

Marine Carbon Dioxide Removal (MCDR) offers untapped potential, leveraging the ocean's vast capacity as a carbon sink. Publishing robust scientific evidence demonstrating no harmful effects, improving Monitoring, Reporting, and Verification (MRV) and enabling regulation can help make MCDR a viable pathway, contributing to the global need for durable carbon removal.

MCDR can be classified into open and closed systems, depending on how carbon is managed and whether it is isolated from the broader environment. Open systems are classed as such because captured CO_2 interacts with the ocean or atmosphere and may release stored carbon over time, whereas closed systems are controlled environments that isolate carbon removal processes. This paper is focused on closed system MCDR only, for the reasons outlined below.

Advantages of Closed System MCDR

Closed system MCDR solutions, for example CO_2 stripping and electrochemical alkalinity production, isolate carbon removal processes. These solutions integrate well with existing coastal infrastructure, offering industrial symbiosis (for example the co-location of desalination plants) and co-benefits such as reduced ocean acidification, which can enhance marine biodiversity.

Additionally, the creation of by-products such as hydrogen, bicarbonates and acid, provides further revenue streams beyond the sale of carbon credits and thus makes for a more robust, lower risk business model. The ocean's scalability reduces land-use conflicts, and some solutions have the potential to eliminate CO_2 storage site dependencies, making closed MCDR systems particularly valuable for regions with limited CO_2 storage options.

In comparison to open systems, Monitoring, Reporting, and Verification (MRV) can be applied with greater certainty and the data is more reliable, which gives a clearer pathway to advancement. This also means results of closed systems are easier to monitor.

Challenges and Necessary Advancements

Currently, there are a number of barriers to the advancement of various MCDR systems, and elements that require addressing before the technology can evolve. Some of these are common challenges, such as cost, while others are related to the specific science or technology involved in the system or regulations.

To scale effectively, closed system MCDR requires:

1. **Robust Science:** Evidence that technologies pose no harm to marine ecosystems, supported by international standards and science-based approaches.

2. **Enhanced MRV and Lifecycle Analysis (LCA):** Standardized protocols ensure credibility, accountability, and a pathway to carbon credit markets.

3. **Cost Reductions:** Current costs of $500–$7,000 per ton must be lowered through energy efficiency, economies of scale, and learning curves.

4. **Regulatory and Incentive Frameworks:** Clear permitting, policy support, and financial incentives are essential to attract investment and accelerate deployment.

Path Forward

Integrating MCDR into the broader CDR portfolio will be critical to achieving 2050 decarbonization targets. Although it is mostly at an early adoption stage, MCDR offers robust potential in terms of scalability and adaptability, which means it is essential that we invest in and advance the technology. By addressing known barriers to developing MCDR systems, for example scientific validation, high costs, and the lack of credible MRV or LCA frameworks, they can become an impactful complement to other carbon removal methods and reach otherwise inaccessible regions and environments.

In All Demand Scenarios, Carbon Dioxide Removal Supply is Very Far from Meeting Demand

Durable carbon dioxide removal (CDR) will play a crucial role in global decarbonization. This was underscored by the emphasis on Article 6 at COP29, where negotiators approved an international framework for carbon credit trading, facilitating the exchange of CDR credits. CDR is important both to counterbalance hard-to-abate sectors and to correct the fact that the world is not on track to meet decarbonization commitments. Every additional ton of CO_2 we are able to remove will help us limit global temperature rise. The IPCC (Intergovernmental Panel on Climate Change) and the IEA (International Energy Agency) estimate that ~2 to ~8 Gtpa of CO_2 will remain unabated in 2050. Our BCG analysis – factoring in abatement costs, economic growth and the fact that we are not deploying decarbonization solutions fast enough – suggests this figure will be even higher, between ~6 and ~10 Gtpa.

In the short term, as per our report, if companies proceed with meeting declared net zero targets, CDR demand could range from ~40–200 Mtpa CO_2 to as high as ~1.1–1.6 Gt CO_2 by 2030. This contrasts sharply with an expected supply of just 15–32 Mtpa.

Despite uncertainties and the slow pace in CDR demand realization (only 12 Mtpa of CO_2 were sold by November 2024[1]), high quality CDR supply is lagging. This means that there is a need to leverage all available solutions to close the expected demand-supply gap.

1. See CDR.fyi for more information: https://www.cdr.fyi/

The Untapped Potential of Marine Solutions

To close the demand-supply gap, many technologies have been developed or are advancing. Land-based solutions (like DACS (Direct Air Capture and Storage); BECCS (Bioenergy with Carbon Capture and Storage); Biochar etc.) are starting to move beyond commercial testing towards small-scale commercial deployment, while ocean-based approaches remain largely underexplored. Despite their higher costs and lower maturity, ocean-centric methods offer some of the highest carbon sequestration potential in the industry. The ocean, as the largest natural carbon sink, has already absorbed 30% of excess CO_2 emissions[2], causing it to become more acidic at the same time as global climate temperatures rise. This is increasingly positioning Marine Carbon Dioxide Removal (MCDR) as a critical frontier for both emission reduction and ocean acidification reduction. MCDR can be classified into three groups, depending on how the CO_2 is captured (Fig. 1):

Fig. 1: MCDR technologies classification

Biogenic		Geochemical	Synthetic	
Living	Stabilized	Dissolved bicarbonate sequestration	Indirect water capture	
Conservation / restoration (Blue carbon)	Micro- and macroalgae cultivation & sinking	Coastal enhanced weathering	CO_2 stripping	Electrochemical alkalinity production
TRL 9	TRL 6	TRL 6	TRL 6	TRL 6
Open system	**Open system**	**Open system**	**Closed system**[1]	**Closed system**
5-15 $/t$CO_2$	150-400 $/t$CO_2$	30-50 $/t$CO_2$	1000-7000 $/t$CO_2$	500-2000 $/t$CO_2$
Energy requirement: **negligible**	Energy requirement: **low**	4-333 kWh / tCO_2	3.1 MWh / tCO_2	2-4.4 MWh / tCO_2

Company Examples:

Conservation / restoration	Micro- and macroalgae	Coastal enhanced weathering	CO_2 stripping	Electrochemical alkalinity production
• Conservation International	• Seaweed Generation	• Planetary Technologies • Vesta	• Captura • CarbonBlue • SeaO₂	• Equatic • Ebb carbon • Limenet

Sources: RMI, The Applied Innovation Roadmap for CDR, 2023; BCG analysis.

[1]Some CO_2 stripping methods can be considered hybrid closed-open system, as part of the CO_2 they capture may be managed in a closed system (e.g. CO_2 stripped from seawater measured and stored in a closed environment), and an additional portion in an open system (e.g. discharged water increases seawater alkalinity, allowing the ocean to absorb more CO_2 from the atmosphere in an open process).

2. See Ocean Visions, Ocean Based Carbon Dioxide Removal: https://oceanvisions.org/ocean-based-carbon-dioxide-removal/

1. **Biogenic MCDR** approaches use natural processes like photosynthesis to capture CO_2 from the atmosphere in marine environments, commonly known as blue carbon. Relevant examples include coastal wetland restoration, marine habitat conservation, and biomass farming/sinking.

2. **Geochemical MCDR** approaches use reactions between CO_2 and alkaline minerals in oceanic settings to store carbon in solid or dissolved forms. A foremost example is coastal enhanced weathering.

3. **Synthetic MCDR** approaches use engineered systems to capture CO_2 directly from the air or modify water chemistry to remove CO_2. Examples include CO_2 stripping and electrochemical alkalinity production.

Fig. 2: Tradeoffs between open and closed MCDR systems

	Open Systems	Closed Systems
Permanence	Lower; CO_2 sequestered through biological uptake (e.g., seaweed or phytoplankton), but decomposition over years to decades can release some CO_2 back to the atmosphere	High; CO_2 stored in stable forms (e.g. minerals, deep-sea formations) for thousands to millions of years
MRV	Challenging; difficult to monitor and verify carbon sequestration over time due to the diffuse movement of CO_2 between ocean and atmosphere	Easier; carbon is stored in well-defined, stable states, making it simpler to track and verify over long-term
Scalability	High; methods like seaweed farming can scale across large areas in near-term horizons	Moderate; constrained by technical complexity and site-specific conditions, but higher impact in the long run
Cost	Lower upfront costs; less expensive to implement but requires ongoing interventions	Higher upfront costs; requires high upfront CAPEX but more cost-effective over time due to permanent carbon storage
Takeaways	**Open systems have lower permanence and challenging MRV, but are cheaper and scalable in the short term**	**Closed systems offer permanent storage but require high initial investment**

MCDR is classified into open and closed systems, based on how carbon is managed and isolated from the broader environment. This classification is important, as the two categories differ in permanence, cost, and ease of MRV.

- **Open systems,** for example algae cultivation and coastal enhanced weathering, are usually scalable and cost effective. They are defined as "open" because captured CO_2 is allowed to exchange with the ocean or atmosphere, meaning stored carbon may be partially released over time, making MRV more complex.

- **Closed systems,** such as CO_2 stripping and electrochemical alkalinity production, are controlled environments that isolate carbon removal processes from the open ocean or atmosphere, allowing for greater control and easier monitoring of carbon sequestration. MRV can be applied with greater certainty and reliability. Nonetheless, they are more expensive and complex to scale due to high CAPEX.

Both open and closed system solutions offer distinct advantages and are essential in addressing CDR supply challenges. However, this report focuses on the key challenges of closed systems due to their clearer path to MRV, which is particularly important for carbon credit commercialization as it is crucial for buyers and standard setters (Fig. 2).

Closed Loop MCDR: Inherent Strengths and Advancements Required

Fig. 3: Inherent strengths and advances required in closed loop systems

Inherent strengths

Industrial symbiosis and byproducts
Co-locating with industry like desalination plants generates valuable by-products, which helps de-risk MCDR projects by providing additional revenue streams

Environmental and social co-benefits
Removing CO_2 can help reduce ocean acidification, potentially providing benefits to marine environments, and boost jobs in coastal areas

Reduced need for CO_2 storage sites
Some MCDR technologies can use the ocean as storage for the captured CO_2 and don't require location near CO_2 storage sites, improving their logistics and scalability

Advancements required

Robust science and evidence of no environmental harm
The current gaps in science, especially about environmental impact, need to be bridged to build robust evidence of no environmental harm

Standardized Monitoring, Reporting, and Verification (MRV)
Standardized MRV and Lifecycle Analysis (LCA) leveraging robust monitoring technologies will provide MCDR the credibility it needs to access voluntary carbon markets

Cost reduction
Open system MCDR approaches have costs of $500-7000/t; scale and energy efficiency will be key to achieve cost competitiveness

Enabling permitting, policy and incentives frameworks
Clarity on permitting, inclusion in relevant policy evolutions, and enabling incentive schemes will help boost Research & Development (R&D) to the extent required for scale-up

Inherent strengths

Closed system MCDR has a series of inherent strengths, which vary depending on the technology used.

Industrial symbiosis and by-products

MCDR naturally integrates with coastal and marine infrastructure, offering opportunities for industrial symbiosis. Coastal assets, such as desalination plants, ports, and offshore renewable energy installations, can support MCDR projects, reducing the need for significant new infrastructure development. For instance, some MCDR technologies can leverage desalination infrastructure by utilizing concentrated brine output to enhance ocean alkalinity for CO_2 sequestration, while also minimizing environmental impact. Additionally, the electrochemical ocean alkalinity process can generate valuable byproducts like hydrogen, acid, or bicarbonates. This enhances the overall economic feasibility of MCDR projects through additional revenue streams and reduces the risk profile of investments by lowering exposure to volatile carbon credit prices.

Environmental and social co-benefits

MCDR can offer significant environmental co-benefits: it can help reduce ocean acidification, which can promote healthier ecosystems, stimulate marine biota, and enhance biodiversity. It can also support sustainable fisheries by improving local water quality, while minimizing land-use competition (compared to other carbon removal solutions like BECCS). Advancements in science and field testing will be needed to determine the extent of positive impact and possible limitations. Moreover, MCDR can also deliver social benefits by creating jobs in areas facing economic challenges, e.g. by leveraging industrial symbiosis and repurposing coastal assets such as decommissioned platforms.

Scalability and reduced need for CO_2 storage sites

MCDR offers significant scalability potential due to the vastness of the ocean, which already absorbs over 10 gigatons of CO_2 annually from over 40 gigatons of anthropogenic emissions[3]. This vast capacity allows MCDR technologies to operate at large scale volumes, avoiding land-use conflicts and spatial limitations.

Moreover, several MCDR approaches bypass the need for dedicated CO_2 storage sites in proximity, making these solutions interesting for locations with limited storage options such as Western Europe, East Asia and Australia. For example, Limenet, a startup focused on ocean-based carbon removal, converts captured CO_2 into calcium bicarbonate, which is stored in the ocean in a stable form. This feature of MCDR reduces logistical challenges and costs associated with locating and managing traditional storage sites, and eases the siting limitations that land-based technologies often face.

Advancements required

While MCDR holds inherent strengths, several advancements are required to fully capitalize on its potential and make it a cost-effective, scalable solution in the global carbon removal landscape.

1. Robust science and evidence of no harmful environmental impact

To unlock the potential of MCDR, it is essential to build a robust scientific foundation proving these technologies have no harmful effect on marine ecosystems. Potential impacts on ocean chemistry, biodiversity, and local marine conditions must be thoroughly understood and managed in order to meet the quality and safeguard thresholds required by international standards, including the ones stated in the recent Article 6.4 approved at COP29. For example, adding alkaline substances to the ocean can enhance CO_2 sequestration, but there is concern that it may also alter pH levels in ways that could affect marine life, from plankton all the way up to larger organisms. Other MCDR methods, such as ocean fertilization or biomass sinking, could inadvertently impact biodiversity or disrupt local currents.

Collaboration between scientists, regulators, and environmental groups is crucial to establish clear internationally-accepted guidelines and ensure MCDR can scale without harming marine environments. Some positive steps in this direction include:

- US National Oceanic and Atmospheric Administration (NOAA) and Department of Energy (DOE) agreement on future research and development collaboration in the field of MCDR

3. See Global Carbon Atlas, Global Carbon Budget, 2023: https://globalcarbonatlas.org/budgets/carbon-budget/

- Ocean Visions Launchpad program (works with startups to measure, understand, and minimize negative environmental effects)

- Ocean Visions' recent launch of research on environmental impact assessment of MCDR[4]

Internationally accepted standards and best practices will be essential to ensure that MCDR projects are designed with environmental safety in mind. Rigorous scientific vetting and transparent guidelines will help build the public's trust and support, which is indispensable for scaling MCDR.

2. Standardized Monitoring, Reporting, and Verification (MRV) and Lifecycle Analysis (LCA)

For MCDR to reach its full potential and scale effectively, robust and credible MRV is essential. Transparent and standardized MRV fosters accountability, builds public trust, and ensures projects can access carbon credit revenue streams from sales in the voluntary carbon market. In closed-system MCDR, precise measurement is achievable but requires commitment from MRV bodies to set rigorous standards.

For marine CDR, conducting lifecycle analysis (LCA) is essential to identify and mitigate any secondary impacts, such as unintended effects on marine biodiversity or local ecosystems, that MRV alone may not capture. While MRV ensures accurate measurement of carbon removal, LCA provides a broader perspective and robustness on the environmental and social consequences of scaling these technologies.

Achieving this rigor requires advanced measurement and monitoring methodologies, supported by technologies like sensors, communications platforms, and oceanographic models to continuously monitor and verify carbon removal and storage. [C]Worthy's C-Star, an open-source tool currently in use by Isometric, enhances MRV credibility for ocean-based CDR by enabling accurate, transparent data collection through sensors, oceanographic modeling, and communication systems - thereby supporting continuous and rigorous monitoring of carbon removal and storage in marine environments.

Standardized carbon accounting across projects is also crucial, as it allows credits from MCDR to access voluntary carbon markets on an equal footing with other methods like DACS, ensuring that 1 ton of CO_2 removed through MCDR is equivalent to 1 ton removed through other technologies.

Recent steps in the right direction, which need to be accelerated, are:

- In June 2024, Isometric published the first protocol for ocean alkalinity enhancement[5] and opened a public consultation on electrolytic seawater mineralization[6].

- Puro.earth launched consultations on protocols for Ocean Storage of Biomass and electrochemical ocean CDR, with results expected by the end of 2024[7].

Without credible and standardized MRV, MCDR will struggle to attract investment, instill stakeholder confidence, and display the robustness needed to be included in emerging policy mechanisms (e.g. the EU's Emission Trading System (ETS)), limiting its impact on climate goals. Establishing strong MRV practices is essential to unlocking the full potential of MCDR.

4. See Ocean Visions, Request for Proposals to Develop Environmental Impact Assessment Framework for MCDR, 2024: https://oceanvisions.org/mcdr-eia-grant/?mc_cid=3c0d2ed79f&mc_eid=aafc732a7c

5. See Isometric, World First Protocol for Ocean Alkalinity Enhancement, 2023: https://isometric.com/writing-articles/world-first-protocol-for-ocean-alkalinity-enhancement

6. See Isometric, A New Protocol for Electrolytic Seawater Mineralization, 2024: https://isometric.com/writing-articles/a-new-protocol-for-electrolytic-seawater-mineralization

7. See Puro.earth, Unlocking the Ocean's Potential for Large-Scale Carbon Removal, 2024: https://puro.earth/blog/our-blog/Unlocking-the-Ocean-s-Potential-for-Large-Scale-Carbon-Removal

3. Cost Reduction

Current costs of CO_2 removal via closed system technologies (e.g. CO_2 stripping; electrochemical alkalinity production) range from $500 to $7000 per ton[8]. This compares to a DACS cost range of between $600 to $1000 per ton, and BECCS of between $50 and $200 per ton.

There are MCDR-specific levers expected to drive down costs:

1. Energy Efficiency: Closed-system MCDR approaches currently use a similar amount of energy per ton of CO_2 removed as DACS (MCDR: ~2–4.4 MWh/tCO_2 vs. DACS: ~2.2–4.9 MWh/tCO_2). Improved hydrodynamics, such as moving loads below the water's surface to reduce drag and energy use, will be a key efficiency gain as MCDR plants move beyond pilot stages.

2. Enhanced MRV: Establishing robust MRV protocols reduces uncertainty discounts and strengthens certainty in captured CO_2 and credit generation, ultimately lowering MRV costs.

Additionally, MCDR, alongside many other emerging technologies will benefit from:

1. Scale Effect: With CAPEX accounting for approximately 70% of total costs - though this varies by technology type - scaling up plant size can reduce CAPEX per ton. This reduction occurs by distributing fixed costs across larger production volumes. Modular systems enhance this effect by enabling cost-effective expansion and flexibility to meet varying project demands.

2. Learning Curve and Experience: Operational improvements and accumulated experience across deployments reduce costs, following the model of learning-by-doing seen in most nascent industries. Feasibility studies, while costly today, apply broadly across different locations and will be a less relevant cost component going forward.

Most existing MCDR startups are targeting a $100 per ton price point within the next five to ten years, driven by these cost-saving measures. However, further advancements in technology and deployment scale are necessary to prove its reachability.

4. Regulatory enablers

Clear permitting, policy, and incentive frameworks are essential to attract investment, reduce risks, and accelerate MCDR development. Although MCDR is less mature than other CDR (e.g., DACS and BECCS), regulatory enablers set today will shape the carbon removal landscape for decades, and MCDR must not be left behind.

Permitting is a critical hurdle for siting MCDR projects. Coastal siting raises environmental concerns, while siting in open waters introduces additional complexity, as the ocean is a shared resource governed by international law. Recent discussions under the London Convention and Protocol have highlighted the need to restrict ocean CDR to protect ecosystems[9]. Removing permitting uncertainty and defining its boundaries is essential for MCDR to scale effectively.

8. BCG analysis based on Stripe project application

9. See IMO, 45th Consultative Meeting of Contracting Parties to the London Convention, 2023: https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/LC-45-LP-18.aspx

On the policy frameworks front, progress toward including CDR in government-sponsored carbon markets is underway, and it's vital that MCDR is part of the conversation. Parties at the COP29 recently approved the UN's Article 6.4 mechanism, including the underlying standard to incorporate all types of carbon removal (both land-based and ocean-based) in the UN-supervised carbon market under the Paris Agreement[10]. In 2023, the US established a Fast-Track Action Committee on MCDR to guide policy and research[11]. However, the EU's Carbon Removals and Carbon Farming (CRCF) Regulation, which is likely to define which CDR technologies can be included in the EU ETS, currently includes DACS and BECCS, but not MCDR[12]. Another notable framework is SBTi (Science Based Target initiatives), which currently acknowledges the roles of land-based carbon removal technologies such as DACS and BECCS as complementary solutions for hard-to-abate sectors. However, MCDR has not yet been incorporated into the SBTi framework. Ensuring a more robust scientific approach, and more solid and standardized MRV and LCA measurements of MCDR, can help enable and accelerate MCDR's inclusion in these frameworks or the creation of dedicated ones, eventually opening up monetization opportunities.

Incentives are also crucial to signal long-term policy support, as support for MCDR is inconsistent. In October 2023, the US Department of Energy awarded $36 million to MCDR-focused MRV projects[13], and made MCDR eligible to compete for a $35 million CDR Purchase Pilot Prize[14]. If a recently proposed bi-partisan bill is passed, MCDR may also be included in the US Inflation Reduction Act's $180-per-ton tax credit for permanent CO_2 storage[15]. Canada's CAD$10 million CDR procurement program is expected to include MCDR[16]. However, MCDR is not eligible for key EU deployment and R&D programs like the Innovation Fund. Denmark's recent $166 million CDR purchase—the largest to date—focused solely on biogenic CDR, ex-cluding MCDR[17]. Incentives are an important component for MCDR enablement and, as previously stated, it is important to focus them on making science around MCDR robust, enabling solid MRV and LCA, to enable first of a kind (FOAK) and industrial scale plants.

10. See United Nations, Requirements for Activities Involving Removals Under the Article 6.4 Mechanism, 2024: https://unfccc.int/sites/default/files/resource/A6.4-SBM014-A06.pdf

11. See Charter of the MCDR-FTAC, 2023: https://www.noaa.gov/sites/default/files/2023-10/mCDR_FTAC_charter_2023_09_19_approved.pdf

12. See European Commission, Carbon Removals and Carbon Farming: https://climate.ec.europa.eu/eu-action/carbon-removals-and-carbon-farming_en

13. See US Department of Energy, DOE Announces $36 Million To Advance Marine Carbon Dioxide Remov-al Techniques and Slash Harmful Greenhouse Gas Pollution, 2023: https://www.energy.gov/articles/doe-an-nounces-36-million-advance-marine-carbon-dioxide-removal-techniques-and-slash

14. MCDR can compete in the category "Planned or managed carbon sinks"; 3 of the 24 semi-finalists announced in May 2024 are essentially MCDR in this category. See US Department of Energy, DOE Announces $1.2 Million To Accelerate America's Carbon Dioxide Removal Industry, 2024: https://www.energy.gov/articles/doe-announces-12-million-accelerate-americas-carbon-dioxide-removal-industry

15. See Carbon Removal Alliance, Creating a Carbon Removal Tax Credit: https://a-us.storyblok.com/f/1020427/x-/36ae8753a8/cdr-investment-act-factsheet-final.pdf

16. Treasury Board of Canada Secretariat, Government of Canada commits to purchase carbon dioxide removal services to green government operations and achieve net-zero emissions, 2024: https://www.canada.ca/en/treasury-board-secretariat/news/2024/10/government-of-canada-commits-to-purchase-carbon-dioxide-removal-services-to-green-government-operations-and-achieve-net-zero-emissions.html

17. See Carbon Herald, Denmark Provides Largest Ever Government Subsidy For Carbon Removal, 2024: https://carbonherald.com/denmark-makes-largest-ever-government-purchase-carbon-removal/

Looking Ahead: Ensuring All CDR Pathways Contribute to 2050 Targets

Ensuring that diverse CDR pathways, including both land-based and ocean-based approaches, can effectively contribute to 2050 decarbonization targets is critical. While MCDR is currently less mature than technologies like DACS and BECCS, they offer potential for scalability and adaptability, especially given the vast storage capacity of the ocean and the flexibility in siting projects. By addressing the existing barriers — scientific validation, credible MRV and LCA frameworks, cost reduction, and creation of adequate regulatory schemes — MCDR can become an indispensable complement to other carbon dioxide removal methods. Failure to integrate MCDR technologies into the broader CDR portfolio risks overlooking a valuable pathway capable of reaching regions and environments inaccessible to land-based technologies. In the context of rising CO_2 concentrations and growing climate pressures, it is essential to invest in and accelerate the advancements of MCDR to ensure a robust, multifaceted approach to global carbon removal.

Appendix: Existing MCDR Solutions

Examples of Open System technologies

Conservation and restoration (blue carbon)

Conservation and restoration of coastal ecosystems, known as blue carbon, involve protecting habitats like mangroves, salt marshes, and seagrasses that absorb CO_2. However, concerns exist around the permanence of these carbon sinks, as they can degrade over time. Blue carbon projects are among the most affordable carbon removal methods, with costs ranging from $5-15 per ton of CO_2. While effective, this approach is mature and well understood, so it is not the focus of this paper.

Micro- and macroalgae cultivation

Micro- and macroalgae cultivation is a technique that involves growing seaweed, such as kelp or sargassum, which absorbs CO_2 through photosynthesis. Once harvested, the seaweed can be sunk into deep ocean waters, sequestering the carbon for extended periods. Beyond capturing CO_2, this process offers additional ecosystem benefits. One company in this space has been focusing on sargassum, an invasive species that clogs coastlines and releases a foul odor as it decays. Capturing and sinking sargassum not only removes carbon but also helps reduce coastal pollution and protect marine habitats. Another notable company has been highly successful in delivering large-scale carbon removals through kelp cultivation. The price range for macroalgae-based CDR typically falls between $150-400 per ton of CO_2 removed, making it a relatively affordable option among marine-based carbon removal strategies.

Coastal enhanced weathering

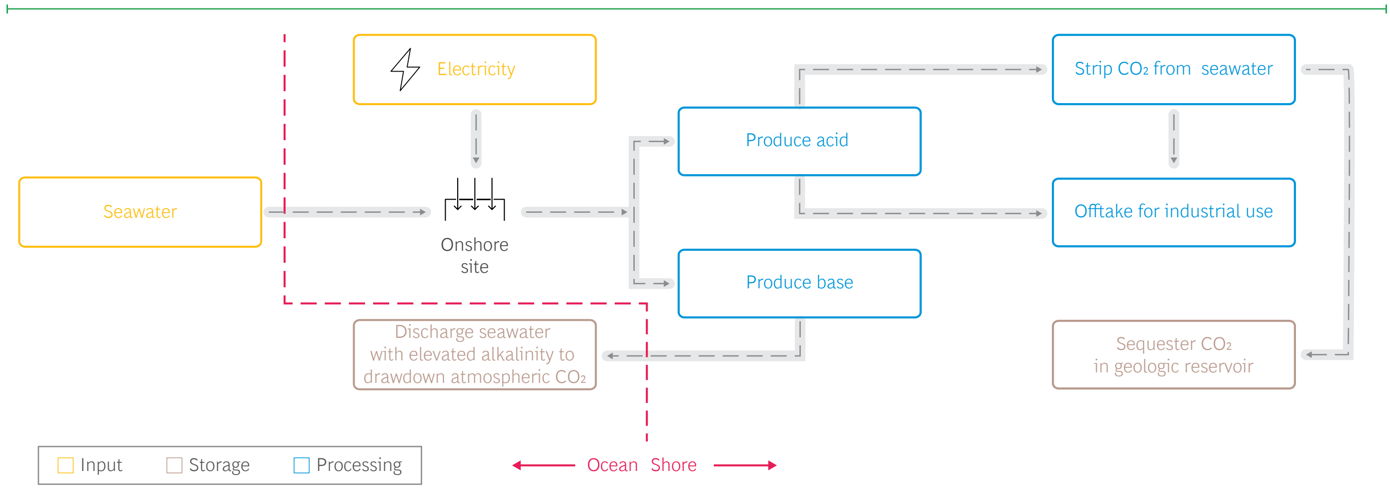
Coastal enhanced weathering is a technique that involves spreading crushed alkaline minerals, like olivine, along coastlines to speed up natural chemical reactions that capture CO_2 from seawater and convert it into stable bicarbonates. This method not only removes atmospheric carbon but also helps combat ocean acidification. The technique itself is low-tech, giving it a significant cost advantage, with removal costs ranging from $30-50 per ton of CO_2—one of the most affordable CDR options. One leading company has been a pioneer in deploying this approach, but there are ongoing concerns about potential ecosystem impacts and public acceptance, particularly in coastal areas where large-scale mineral deployment could affect local habitats. Despite these challenges, coastal enhanced weathering remains a promising and cost-effective solution for ocean-based carbon removal.

Examples of Closed System technologies

CO_2 stripping

CO_2 stripping is a technique that involves removing dissolved CO_2 directly from seawater using chemical or electrochemical processes. The extracted CO_2 can then be stored permanently in secure geological formations underground, sequestered in stable mineral forms, or used in various industrial applications. By selectively removing CO_2 from seawater, this approach also allows the ocean to absorb more CO_2 from the atmosphere, enhancing its natural carbon sink capacity and helping to counteract ocean acidification. The potential harmfulness of this process varies widely. If CO_2 is removed from the ocean, this will increase its pH level and counter the trend of ocean acidification. However, if bicarbonate and carbonate ions are also removed, water will become more sensitive to acidification. CO_2 stripping has several advantages over techniques that remove CO_2 from the atmosphere instead, such as direct air capture (DAC), including higher CO_2 concentrations and easier integration with offshore storage or utilization options. However, CO_2 stripping is still in the early stages of development and faces technical challenges such as corrosion, fouling, scaling, and environmental impacts. It is a low-maturity technique, with a cost estimate of $1000-$7000[18] per ton of CO_2 removed (Fig. 3).

Fig. 3: CO_2 stripping



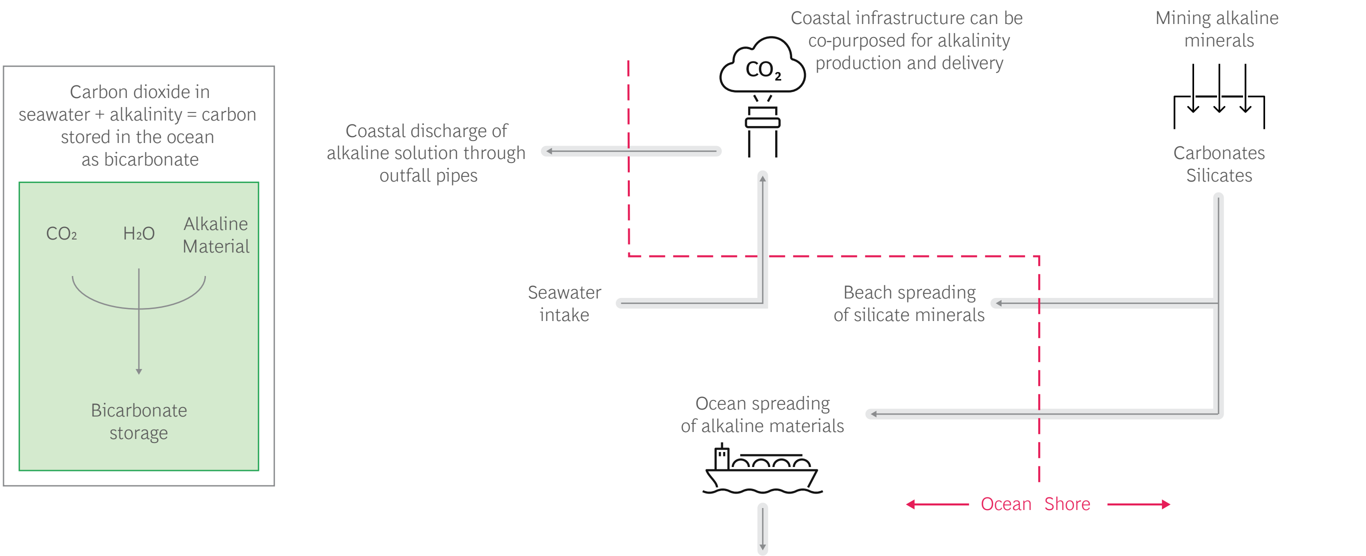
One startup operating in the CO_2 stripping industry plans to use floating platforms that can remove CO_2 from the ocean. It uses an electrochemical process to extract CO_2 directly from seawater without adding chemicals. This CO_2 is then available for permanent storage via secure underground storage solutions. The process returns de-carbonated seawater to the ocean, enabling it to absorb more atmospheric CO_2, thereby enhancing the ocean's natural carbon sink capacity.

Electrochemical alkalinity production

Electrochemical alkalinity production is a technique that involves increasing the pH and carbonate ion concentration of seawater by adding alkaline substances such as limestone, olivine, or sodium hydroxide. This enhances the ocean's natural capacity to absorb and store CO_2 from the atmosphere while also mitigating ocean acidification. Electrochemical alkalinity production can be applied at various scales and locations, such as coastal watersheds, estuaries, or the open ocean. However, electrochemical alkalinity production also faces technical challenges such as material sourcing, transportation, and dissolution, as well as environmental impacts such as changes in marine chemistry, biology, and ecology. Since it directly alters the acidity of seawater, this solution can have critical impacts on marine biodiversity. It is a low-maturity technique, with a cost estimate of $500-$2000 per ton of CO_2 removed[19].

18. BCG analysis based on Stripe and company websites
19. BCG analysis based on Stripe and company websites

Fig. 4: Ocean alkalinity enhancement



One startup in the alkalinity enhancement field has developed a modular system that can be integrated into desalination plants and coastal industry plants. This technology treats water before it is discharged into the sea by extracting acid from the brine flow (which can then be sold as a product). The treated seawater is then returned to the ocean with slightly higher alkaline levels, where it reacts with CO_2 from the air to form bicarbonate, while also reducing water acidity.

Another company uses calcium carbonate, marine water, and renewable electric energy to convert carbon dioxide, sourced from the atmosphere or other sources, into an aqueous solution with a marine pH 8.15, primarily composed of calcium bicarbonates. This innovative process results in a robust and stable solution for storing CO_2 within the world's seas and oceans.

Another active player in this space is using a novel electrolytic method to extract CO_2 from the ocean, allowing it to absorb more CO_2 from the air. It achieves two goals that are essential for a low-carbon economy: (1) locking up CO_2 permanently in the ocean, as bicarbonate ions (in water) or solid mineral carbonates; (2) generating hydrogen, a green fuel that can replace fossil fuels and help avoid further CO_2 emissions. Since both products share the same infrastructure and capital investment, it can offer unique cost advantages, another driver of a low-carbon economy. The startup has already sold all the carbon dioxide it can currently remove through pre-purchase agreements with major customers.

Another player in the MCDR space is utilizing technology designed to boost the ocean's natural capacity to absorb CO_2. Its process utilizes an electrochemical method to increase the alkalinity of seawater by treating the brine discharge from desalination plants. This approach creates a more alkaline environment that enables seawater to absorb CO_2 from the atmosphere, converting it into stable bicarbonate ions stored in the ocean. The treated, more alkaline seawater is then returned to the ocean, helping to sequester CO_2 and simultaneously counteract ocean acidification.

In addition to enhancing alkalinity, this process generates valuable byproducts, such as acid and bicarbonates, which can be used in various industrial applications or sold as additional revenue streams. By leveraging existing desalination infrastructure, this approach reduces the need for new installations, minimizes environmental discharge impacts, and supports more economically viable, scalable CO_2 removal in coastal regions. This integration with desalination exemplifies how MCDR technologies can align with existing infrastructure to provide both environmental and economic benefits.

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