MECHANISMS OF MARINE CO2 ABSORPTION AND CDR TECHNOLOGIES

— POTENTIAL SOLUTIONS FOR CLIMATE CHANGE AND BIODIVERSITY —

Yuji Inada
Industry Innovation Dept., Technology & Innovation Studies Div.
Mitsui & Co. Global Strategic Studies Institute

SUMMARY

- The oceans absorb more atmospheric CO_2 than anything on land. CO_2 removal (CDR: Carbon Dioxide Removal) is primarily promoted on land through afforestation and soil storage, but technological development is underway to utilize the oceans, which cover 70% of the Earth's surface.
- Removal technologies that make use of the ocean's ability to absorb CO_2 are called marine CDR technologies, and there are three major types: direct marine capture, biomass fixation, and enhanced weathering.
- These technologies are still under development, and commercialization is expected to take at least another five years. Their costs are also unknown. However, they are likely to come into the limelight in conjunction with the Nature Positive initiative because, in addition to removing CO_2, they will also aid in preserving marine biodiversity and preventing acidification.

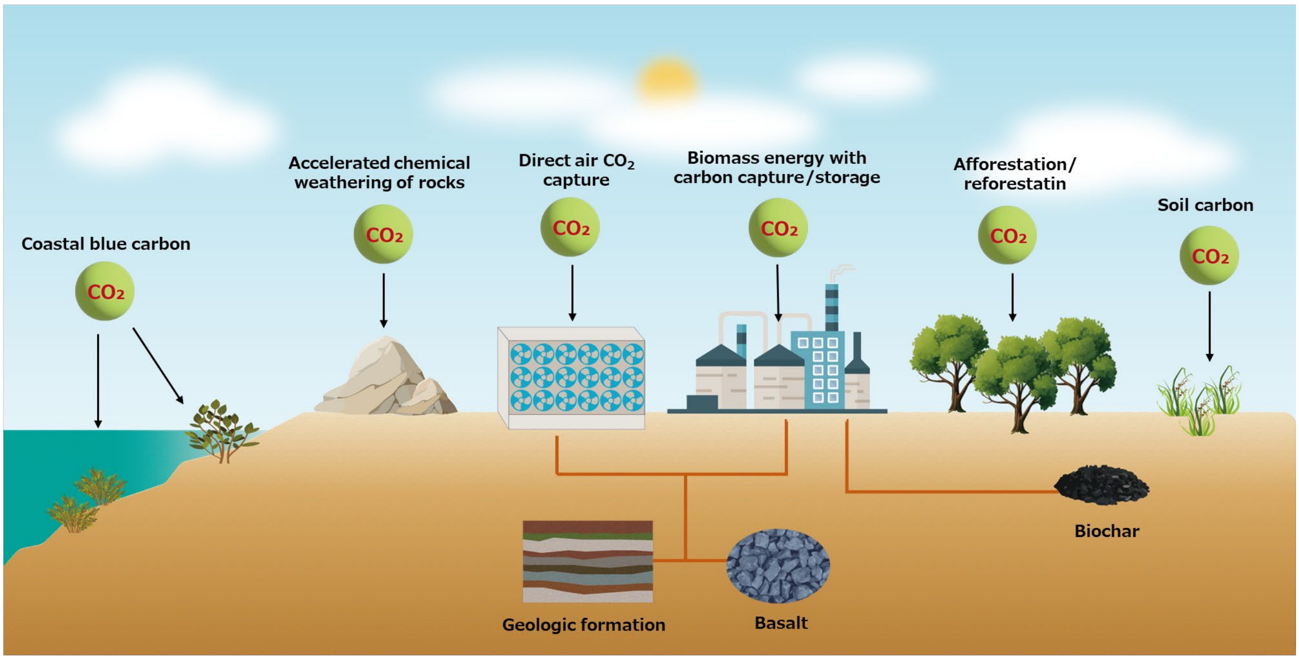
1. WHY IS MARINE CO2 ABSORPTION ATTRACTING ATTENTION?

1-1. CDR is a key technology for achieving carbon neutrality

CDR technologies are designed to capture and absorb atmospheric CO_2 for storage and fixation. The goal is to accelerate the natural processes of CO_2 absorption and fixation by incorporating anthropogenic processes. Achieving carbon neutrality by 2050 will inevitably require offsetting CO_2 emissions, in which CDR technologies are essential. There exists a broad range of technologies, including afforestation and reforestation, soil carbon storage, biomass carbonization, bioenergy with carbon capture and storage (BECCS[1]), direct air capture with carbon storage (DACCS[2]), enhanced weathering, and CO_2 fixation using seaweeds and sea grasses (Figure 1).

[1] BECCS: Biomass Energy with Carbon Capture and Storage
[2] DACCS: Direct Air Carbon Capture and Storage

Figure 1: Various CDR technologies

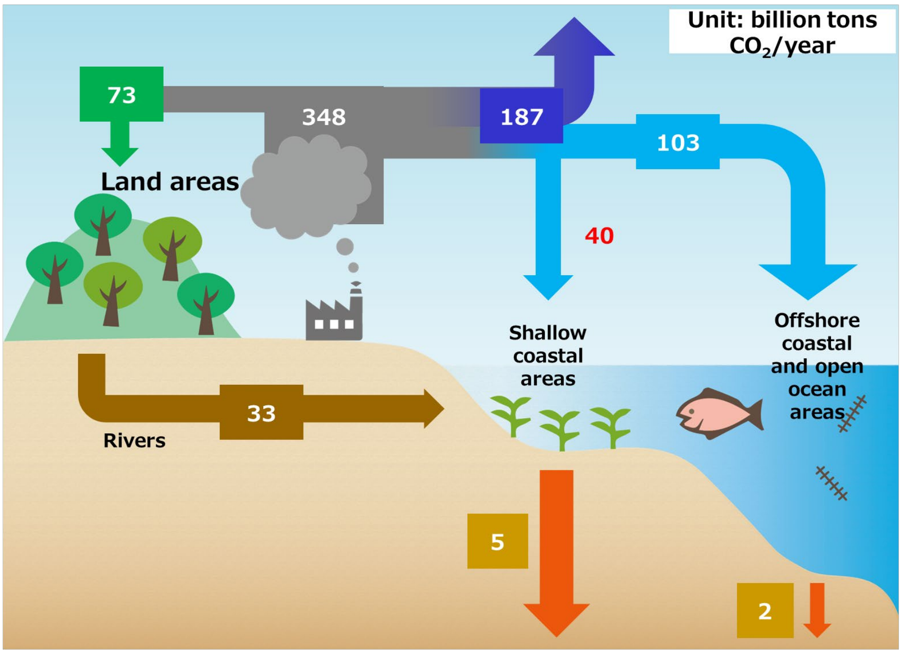


Source: National Academies Press, Negative Emissions Technologies and Reliable Sequestration: A Research Agenda (2019), Chapter:1 Introduction https://nap.nationalacademies.org/read/25259/chapter/3 (accessed December 15, 2023)

1-2. Expectations of marine CO_2 absorption and marine CDR technologies

CDR technologies thus far have been primarily for use on land. However, of the 34.8 billion tons of CO_2 released into the atmosphere annually, only 7.3 billion tons are absorbed on land, while far more—10.3 billion tons—are absorbed by the ocean (Figure 2). Thus, the ocean absorbs an enormous amount of CO_2[3].

Figure 2: Atmospheric CO_2 emissions and volume of absorption by land and sea



Source: Compiled by MGSSI based on Japan Blue Economy Association "A Guide to Applying for J Blue Credit® Certification, Kuwae and Crooks (2021)" [in Japanese] https://www.blueeconomy.jp/wp-content/uploads/jbc2023/20230816_J-BlueCredit_Guideline_v2.3_rev_his.pdf (accessed December 15, 2023)

[3] Mangroves, marshy wetlands, seagrass beds, and other marine ecosystems that thrive in coastal areas are major carbon sinks.

The Intergovernmental Panel on Climate Change (IPCC), which studies climate change countermeasures, is also paying attention to marine CO_2 absorption. In its Sixth Assessment Report, the panel noted that the conservation and restoration of marine ecosystems has "high cost-effectiveness and generates multiple co-benefits" as a climate change mitigation measure[4].

2. WHAT ARE MARINE CDR TECHNOLOGIES?

2-1. Mechanisms of marine CO_2 absorption

While the mechanisms by which the ocean absorbs CO_2 are complex, they can be broadly classified into three categories: (1) direct dissolution, (2) biomass fixation, and (3) chemical fixation.

The first, direct dissolution (Figure 3(1)), refers to the dissolution of atmospheric CO_2 into the ocean as the atmosphere is stirred by winds and waves across the surface of the ocean. The amount of CO_2 that dissolves into the seawater is influenced by the environment, such as the temperature and salinity of the seawater at a particular location. Generally, CO_2 concentrations are high where the seawater is low in temperature and high in salinity. According to observations over the ocean south of Japan by the Japan Meteorological Agency, surface seawater has a CO_2 concentration of roughly 360 ppm[5]. The increasing volume of CO_2 in the ocean, as well as in the atmosphere, is a concern as it increased by approx. 40 ppm from the 1980s to 2015[6].

The second, biomass fixation (Figure 3(2)), occurs when phytoplankton, seaweeds, and other organisms take in the CO_2 dissolved in seawater as organic matter (a compound of carbon, oxygen, and hydrogen) in the process of photosynthesis. This organic matter is then ingested and spread through the food chain as the phytoplankton, seaweeds, etc. are eaten by fish, shellfish, and other organisms. Some of this organic matter settles on the seafloor where it lies dormant for a long period of time, meaning that the CO_2 is also stored on the seafloor.

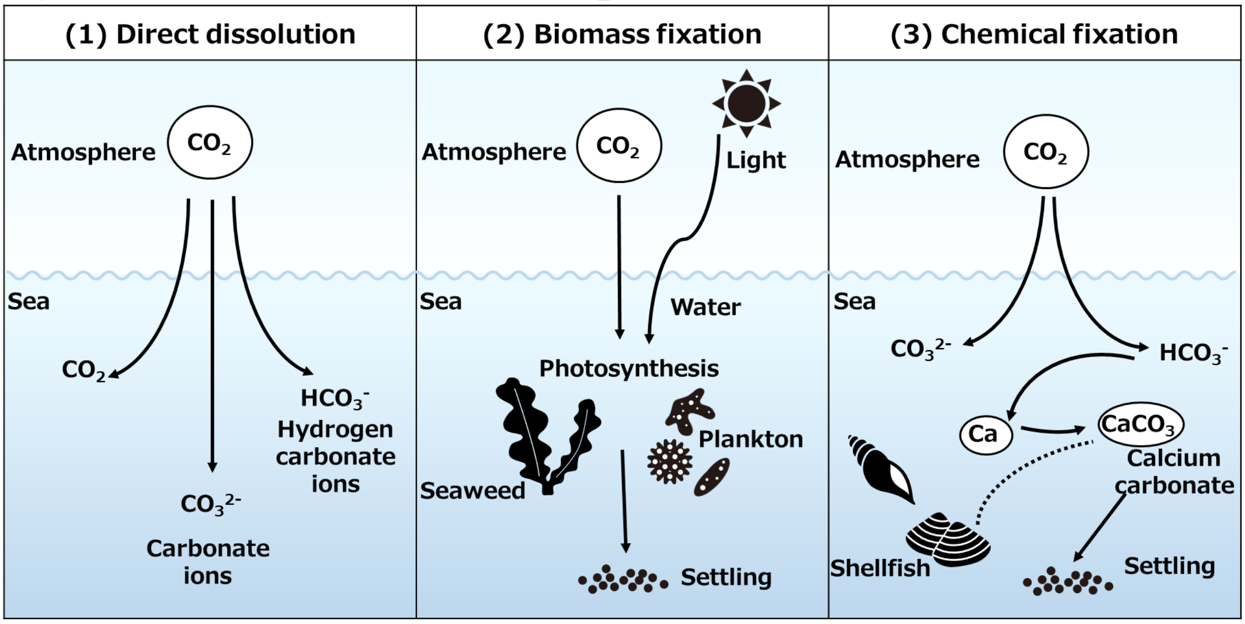
The third, chemical fixation, is a mechanism in which the CO_2 dissolved in seawater becomes stored through chemical reactions with other substances (Figure 3(3)). As seen in the direct dissolution process, CO_2 in seawater reacts with the water to form ions such as hydrogen carbonate ions (HCO_3^-) and carbonate ions (CO_3^{2-}). These ions react with the calcium and magnesium present in seawater to form compounds. These compounds then store the CO_2 by either floating in the ocean or settling to the seafloor. Living organisms also play a role in chemical fixation, similar to the mechanism by which shellfish form calcium carbonate shells.

4 The report warns that the decrease and destruction of marine ecosystems is being accelerated by the impact of climate change and human activities, leading to increased atmospheric CO_2 and reduced biodiversity, and states that conservation and restoration are also effective means of adapting to the effects of climate change. There is also a trend among international research institutions, such as the World Resources Institute (WRI), to view the ocean as a new CO_2 storage sink.

5 "ppm" (parts per million) is a unit indicating one part per million. One ppm is equivalent to 0.0001% and 10,000 ppm is 1%.

6 CO_2 concentrations in the Northwest Pacific region, which includes Japan (Japan Meteorological Agency)

Figure 3: Mechanisms of marine CO_2 absorption



Source: Compiled by MGSSI

2-2. Types and characteristics of marine CDR technologies

The volume of marine CO_2 absorption is actually related to a complex set of factors, including the physical and chemical relationships between the ocean and the atmosphere, and the degree of marine organism activity. While accurately determining the volume of marine CO_2 absorption over a wide area would be a difficult task with current technology, it is an undeniable natural principle that an increase in the ocean's ability to absorb CO_2 will increase the volume of CO_2 absorbed from the atmosphere. If marine CDR technologies are able to reduce the CO_2 in seawater, it will enable the ocean to absorb a higher volume of atmospheric CO_2.

This report introduces the three marine CDR technologies of (1) direct ocean capture, (2) biomass fixation, and (3) enhanced weathering, which correspond to the three mechanisms of marine CO_2 absorption.

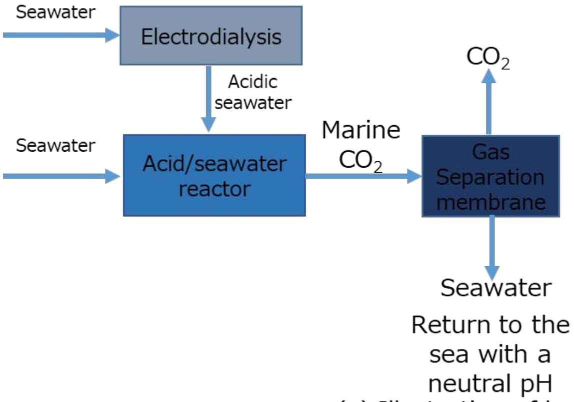
(1) Direct ocean capture

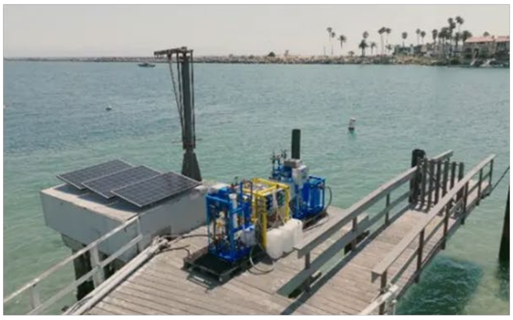
The technology of direct ocean capture (DOC) recovers the CO_2 and carbonate ions dissolved in seawater via electrochemical methods, and it corresponds to the process of direct dissolution previously mentioned. It uses electricity to stimulate a chemical reaction in seawater, causing it to release CO_2.

Captura Corp. (US) is developing a technology in which acidic seawater is produced via electrodialysis and mixed with ordinary seawater to cause the release of CO_2, which is then efficiently captured using a gas separation membrane (Figure 4(a)). The company is currently developing a small-scale test device to capture 1 ton of CO_2 annually (Figure 4(b)), and plans to conduct a pilot test at the Port of Los Angeles with funding from Southern California Gas to capture 100 tons of CO_2 annually. In the future, the company envisions installing large-scale facilities offshore (Figure 4(c)). Other companies such as Heimdal (US) and Ebb Carbon, Inc. (US) are also developing direct ocean capture methods.

Figure 4: Captura's direct ocean capture method

(a) Conceptual diagram of capturing CO_2 by membrane via electrolysis of seawater
(b) Test device for capturing 1 t-CO_2/year





(c) Illustration of large facility to be installed at sea

Source: (a) Compiled by MGSSI based on Captura material "Carbon Dioxide Removal Pathway: Ocean Health and MRV"
https://capturacorp.com/wp-content/uploads/2023/10/Captura-Carbon-Dioxide-Removal-Pathway.pdf
(b) and (c) Captura's website (https://capturacorp.com/) (accessed December 15, 2023)

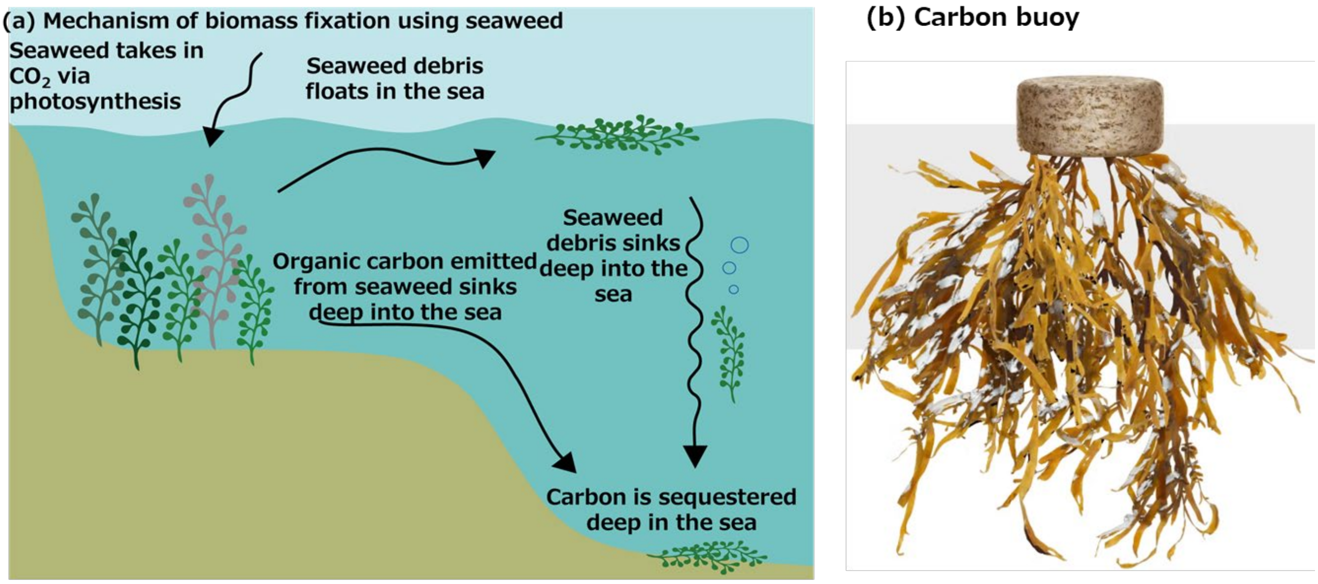
(2) Biomass fixation

The technology of biomass fixation cultivates seaweed on the ocean surface, which grows by absorbing the CO_2 in seawater via photosynthesis, and after a certain period of growth, sinks to the seafloor to store the CO_2 (Figure 5(a)).

Running Tide (US) is developing a technology that uses special floats called carbon buoys (Figure 5(b)) to grow seaweed in the ocean, which is then sunk to the seafloor to remove CO_2.

Carbon buoys are designed to move up and down in the ocean in response to environmental conditions, such as seawater temperature and salinity, and when the seaweed is sufficiently grown, to detach it from the buoy and let it sink naturally. The company asserts that, with the seaweed sinking deep into the sea, the CO_2 absorbed during photosynthesis will be sequestered semi-permanently.

Figure 5: Running Tide's biomass fixation method



Source: (a) Compiled by MGSSI based on Harvard University GRAS website "How Kelp Naturally Combats Global Climate Change"
https://sitn.hms.harvard.edu/flash/2019/how-kelp-naturally-combats-global-climate-change/
(b) Lune Climate website "Amplifying nature's climate solution – a deep dive on ocean carbon removal"
https://lune.co/blog/deep-dive-on-ocean-carbon-removal-ft-running-tide/ (accessed December 15, 2023)

(3) Enhanced weathering

The technology of enhanced weathering applies a mineralization reaction in which magnesium and calcium in olivine, a type of mineral, combine with CO_2 in the atmosphere and seawater to form a compound. This phenomenon is called enhanced weathering because it is the same process by which minerals in nature are weathered.

Project Vesta (US) is developing a technology that uses a reaction in which olivine combines with CO_2 to form a magnesium compound (Figure 6(a)). Crushed olivine is spread along the coast to remove CO_2 (Figure 6(b)). Removing a large volume of CO_2 requires spreading over a large area, and the most suitable method is to spread it in coastal areas. This method is capable of removing CO_2 from both seawater and the atmosphere. The company is currently conducting field tests in North Carolina and on the Island of Hawaii. The company has also announced plans to mine in the Sultanate of Oman and the United Arab Emirates, where olivine is abundant, for spreading in coastal areas in the Middle East[7]. The technology of enhanced weathering is applicable beyond just the US or the Middle East. It can be adopted anywhere that minerals can be procured inexpensively and locations for spreading can be secured, so it has the potential for broad use around the world.

[7] In Japan, the New Energy and Industrial Technology Development Organization (NEDO) worked to fix CO_2 by spreading basalt under the Moonshot Research and Development Program in 2022. Waseda University, Hokkaido University, Mitsubishi Heavy Industries Engineering, and others are driving the development of this technology. However, instead of removing marine CO_2, development is primarily aimed at removing atmospheric CO_2 by spreading basalt in quarries, agricultural lands, and closed mines.

Figure 6: Project Vesta's enhanced weathering method

(a) Mechanism of enhanced weathering using olivine (b) Illustration of spreading along the coast

Source: (a) Compiled by MGSSI
(b) INDIEGOGO website, Project Vesta - Turning the Tide on Climate Change
https://www.indiegogo.com/projects/project-vesta-turning-the-tide-on-climate-change# (accessed December 15, 2023)

2-3. Costs, characteristics, and challenges of marine CDR technologies

Figure 7 summarizes examples of companies engaged in each type of marine CDR technology, along with their CO_2 reduction costs, characteristics, and challenges.

The direct ocean capture method is expected to have a CO_2 reduction cost of 300 to 500 dollars per ton of CO_2. Since the CO_2 in seawater is extracted as a gas through electrochemical and membrane technologies, it is clear how much CO_2 is removed. At the same time, however, the system is complex and requires energy to drive the equipment, making it more costly than other marine CDR technologies.

The biomass fixation method costs less than 50 dollars/t-CO_2, and the cost is kept down because the seaweed is allowed to grow in a natural marine environment. On the other hand, the volume of CO_2 that can be stored long-term by sinking the seaweed deep into the sea has yet to be scientifically proven. The impact of the submerged seaweed on the deep-sea environment is also an issue that has yet to be clarified.

The enhanced weathering method is assumed to cost 100 to 125 dollars/t-CO_2, which is less costly than the direct ocean capture method because the dispersed ore absorbs CO_2 in the natural environment. However, as with biomass fixation, it is difficult to determine the volume of CO_2 that can be removed from the ocean because the volume of CO_2 fixed by the ore depends on the environment where it is spread, and the long-term environmental impact on the coastal areas where it is spread is also currently unclear.

Although each method has its own technical challenges, the direct air capture (DAC) method is projected to cost 500 to 600 dollars per t-CO2, while marine CDR technologies are expected to be even less expensive. If these costs can be achieved during commercialization and the technical issues can be resolved, marine CDR technologies could be widely used.

Figure 7: Costs, characteristics, and challenges of marine CDR technologies

Marine CDR technology	Examples of companies	CO_2 reduction cost (dollars/t-CO_2)	Characteristics and challenges
Direct ocean capture	Captura (US), Heimdal (US), Ebb Carbon (US)	300 - 500	・CO_2 is extracted from seawater as gas, so the volume of CO_2 is clear. ・High cost due to its complex system and need for power.
Biomass fixation	Running Tide (US), Brilliant Planet (UK)	50 or lower	・Low cost due to use of the natural environment. ・The seaweed-based CO_2 fixation volume remains undetermined. ・Environmental impact on the deep sea remains unclear.
Enhanced weathering	Project Vesta (US), Cquestr8 (UK)	100 - 125	・Low cost due to use of the natural environment. ・The ore-based CO_2 fixation volume remains undetermined. ・Environmental impact on marine coasts remains unclear.

Source: Compiled by MGSSI based on various sources

3. FUTURE PROSPECTS

The challenges facing marine CDR technologies include cost, quantification and standardization of the volume of CO_2 reduced, and clarification of their impact on marine ecosystems. Furthermore, the biomass fixation method may lead to illegal waste dumping if seaweed settles too deep into the sea, creating regulatory barriers.

To clarify and solve these issues, the US Department of Energy has launched the Marine Carbon Dioxide Removal Techniques program. In addition, through the SEAO2-CDR program, EU Horizon Europe is also supporting the academic institutions and startup companies that are driving development. These programs aim to assess the mechanisms and quantification of CO_2 fixation and investigate the impact on marine ecosystems, which will likely provide a path toward clarifying and resolving these issues.

At this stage, it is premature to expect commercialization of marine CDR technologies any time soon, since it is expected to take at least five more years to sort out which technologies will make it to commercialization, and realization is not expected until 2030 or later.

Meanwhile, if they are proven to have a positive impact on preventing marine acidification and on marine ecosystems, they could be used to restore and conserve the marine environment while reducing CO_2. Given the current emphasis on climate change measures, natural capital, and biodiversity, marine CDR technologies may be a promising solution. Therefore, future trends must be closely monitored.