OCEAN CARBON DIOXIDE REMOVAL METHODS

AUTHORS:

James R. Collins, Marine Biogeochemical Scientist, EDF

Sarah R. Cooley, Director of Climate Science, Ocean Conservancy

Lisa Suatoni, Deputy Director Oceans, NRDC

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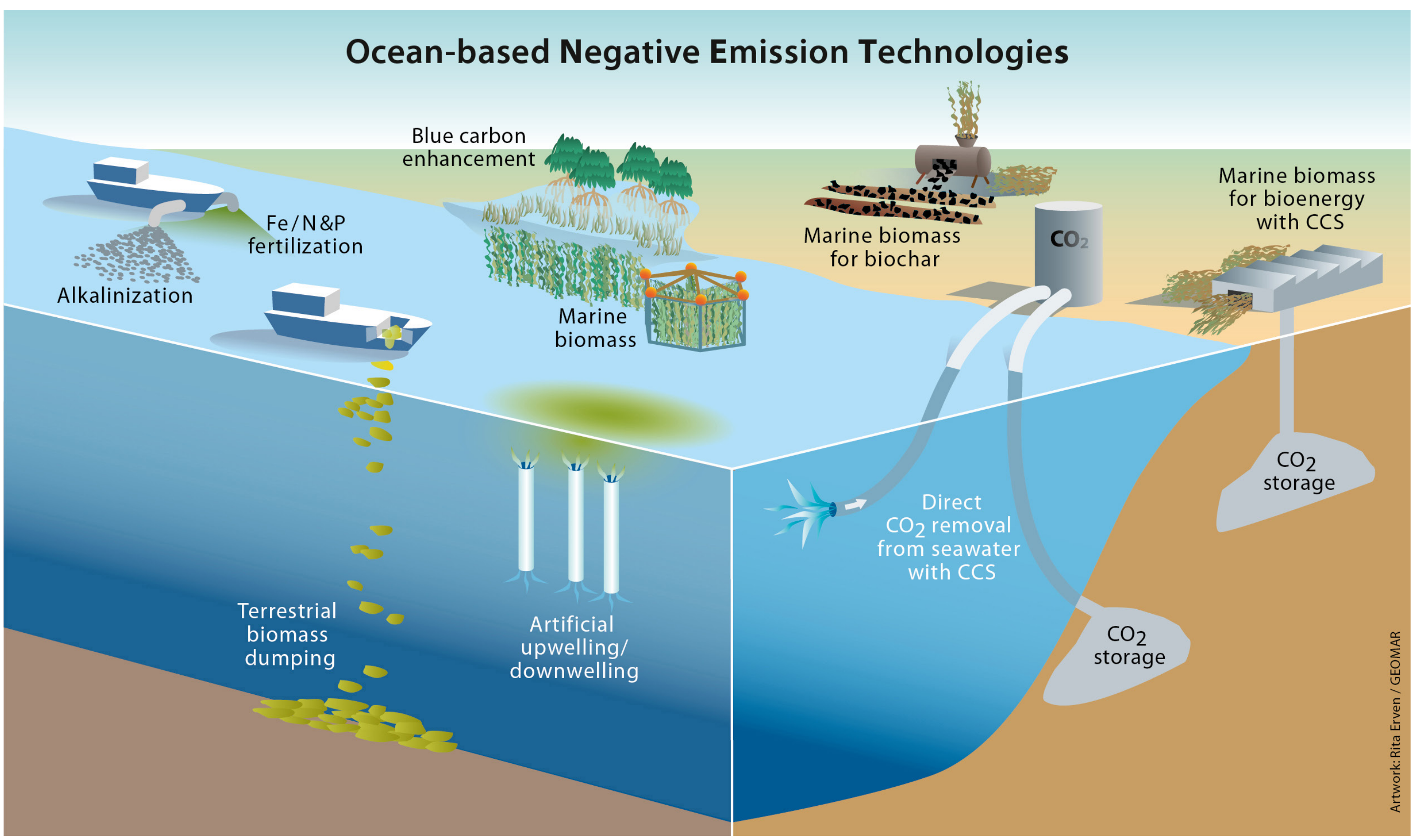
What Is Ocean Carbon Dioxide Removal?

All future climate scenarios that hold planetary warming close to 1.5 °C by 2050 will require massive cuts in greenhouse gas emissions, supplemented by the use of carbon dioxide removal (CDR) methods to clean up leftover heat-trapping carbon dioxide (CO_2) from the atmosphere.[1] The ocean has already naturally absorbed almost 30 percent of all CO_2 emissions caused by humans between 1800 and 1994, and many people are interested in deliberately increasing this uptake using ocean CDR techniques.[2] These techniques seek to protect or enhance natural biological and geochemical processes in order to manipulate the Earth's carbon cycle and counteract this primary driver of climate change (Figure 1). Approaches include conservation or restoration measures to increase natural stores within blue carbon ecosystems—for example, by restoring coastal wetlands—as well as technological approaches that increase the ocean's carbon storage capacity. However, with the exception of the blue carbon methods described in this booklet, most ocean CDR techniques have not been tested at scale, and a few are essentially still on the drawing board.[3]

There is insufficient evidence to determine if most ocean CDR techniques can substantially and durably draw down anthropogenic CO_2, if the societal impacts of these actions would be equitably distributed, and, in the case of technological approaches, if ocean CDR would pose fewer risks for natural and human systems than CDR in atmospheric or terrestrial locations. The research or deployment of technological CDR in the ocean, which is shared by billions of people, could pose significant risks for equity, environmental justice, ecosystem health, food security, and human livelihoods.

Figure 1: Several of the ocean CDR techniques being advanced[4]



Multidisciplinary research is needed to explore all technological ocean CDR methods. Research must go beyond examining simply how much additional CO_2 can be captured and stored in the ocean and what it will cost; it must also include an evaluation of environmental and social risks and co-benefits.[5]

Additionally, given the potential social and environmental risks associated with field research, a research code of conduct should be developed and all recipients of federal grants should be required to adopt it. There should also be incentives for scientists performing CDR research supported by private funding to do the same.[6] This code of conduct should address fundamental principles of scientific integrity (e.g., transparency and dissemination of results), fairness and equity (e.g., public consultation), and responsible research (e.g., minimization of potential harms and assignment of responsibility) across all ocean-based CDR methods.

Ocean-based CDR is a nascent field and is garnering a lot of attention. However, CDR cannot substitute for rapid and deep cuts in greenhouse gas emissions. The development and potential use of these techniques can be only one piece of a comprehensive and equitable climate strategy. This booklet provides a primer on various ocean CDR strategies, summarizing the theory behind each technique, the current state of knowledge of their carbon storage potential and associated costs, technical readiness, and potential environmental and social impacts.

Endnotes

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Blue Carbon: At a Glance

"Blue carbon" methods are a wide-ranging category of nature-based climate solutions that aim to preserve or enhance the ocean's natural CO_2 capture and storage capacity by protecting, restoring, or better managing specific ocean ecosystems. These include the conservation and restoration of coastal blue carbon ecosystems such as mangroves, salt marshes, seagrasses, and naturally occurring kelp forests, as well as approaches based on rebuilding populations of various fish species and great whales by reducing harvests or other key stressors.[7] When these methods involve restoring damaged ecosystems or rebuilding the populations of animals that have been previously harvested or hunted by humans, they are referred to as blue "ecosystem recovery" methods. A critical feature of these methods is their ability to produce a host of valuable co-benefits for both human society and nature, many of which can be realized even if the amount of carbon sequestered in a particular instance is small. Compared with many technological CDR approaches, the ecological risks associated with blue carbon methods are judged to be extremely low.[8]

Potential Scale of Carbon Storage: Estimates of the amount of carbon that can be stored via these approaches vary widely; several different methods fall into this category of CDR, and each has its own potential contribution and unique sources of scientific uncertainty. One recent study concluded that pathways based on rebuilding whale and fish populations could remove 0.02–0.3 gigatonnes of carbon per year (GtC yr^{-1}).[9] Meanwhile, restoration of mangroves and salt marshes could net an additional 0.008–0.3 GtC yr^{-1} in new storage relative to present-day baselines.[10] Conservation of existing mangroves, salt marshes, and seagrass beds globally would avoid about 0.08 GtC yr^{-1} in new emissions.[11] The potential scale of carbon dioxide removal based on these coastal blue carbon ecosystems is limited in part by the relatively small spatial area they occupy relative to the ocean as a whole.[12]

Duration of Carbon Storage: As with storage capacity, estimates of the timescale of sequestration vary widely across blue carbon methods. The carbon transported to the deep ocean and seafloor in dead matter such as kelp fronds and the carcasses of whales and fish can be reliably sequestered from the atmosphere for more than 100 years at depths below 1,500 meters, and for timescales of more than 1,000 years upon reaching the deepest ocean depths.[13] Some carbon can be stored in mangrove, salt marsh, and seagrass soils for centuries, though the fate of this carbon is increasingly uncertain in the face of climate-driven changes in sea level, frequency and severity of major storms, and changes in species ranges.[14]

Cost: Mangrove restoration can remove CO_2 for $1,800 per ton C.[15] The conservation of existing mangrove stands can be accomplished for as little as $37 per ton C.[16] Costs for most other blue carbon pathways are not as well understood, with estimates ranging from $17 to $40,820 per ton C.[17] There are no existing per-ton cost estimates for sequestration based on rebuilding fish or whale populations.

Technical Readiness: Methods for restoration of mangroves and salt marshes are well developed and increasingly cost effective, though the cost of these projects often cannot be justified on the basis of CO_2 removal alone. However, cost may be justified when other ecosystem benefits, such as the protection of fish nurseries, are considered. Restoration of seagrass beds is expensive and at times ineffective, and there is significant uncertainty as to whether seagrasses store more carbon than they release; at least one study has concluded there is little to no cost-effective potential in large-scale seagrass restoration as a carbon removal solution.[18] There are no existing carbon market standards for CDR via rebuilding of fish or marine mammal populations. It is additionally not clear, in the case of many whales, what policy interventions could be imposed to support species growth beyond naturally occurring rates. However, this does not negate the benefits of efforts to rebuild the populations of these animals for reasons other than carbon sequestration.

Potential Risks and Benefits (Social and Environmental): The co-benefits of blue carbon CDR methods are among these approaches' greatest strengths relative to technological approaches. They include physical protection against storms and coastal erosion, increased resilience of ecosystems in the face of climate change through increased biodiversity, provision of food for growing human populations, and support of human livelihoods in industries as diverse as outdoor recreation, agriculture, and marine operations.[19] Social and governance challenges may be less significant than with other CDR approaches because of general public support for ecosystem conservation and positive synergy with existing environmental protection laws. However, any blue carbon CDR method should be accompanied by projects or policy interventions to ensure that the benefits are distributed equitably to avoid the serious injustices that accompanied many carbon crediting projects conducted under the original Reducing Emissions From Deforestation and Forest Degradation (REDD) framework.

Outstanding Questions: A significant challenge for all blue carbon–based CDR pathways is monitoring, reporting, and verification (MRV) of the quantity and durability of carbon stored, especially considering the unpredictability of climate change and human development patterns. There are also substantial uncertainties surrounding emissions of other greenhouse gases, including methane, from mangroves and salt marshes; in some cases, these emissions could severely limit the climate mitigation potential of these ecosystems.[20] The amount of carbon that fish and marine mammals help sequester from the atmosphere has not been quantified with precision, making animal-based pathways the least ready for deployment of the natural CDR methods. However, there is ample scientific evidence that conserving existing fish and whale populations produces multiple co-benefits and can help us avoid substantial new CO_2 emissions from the ocean.[21]

7 The establishment of new seaweed farms in the offshore environment, a CDR method known as ocean afforestation, is covered separately in the companion chapter "Macroalgal Open-Ocean Mariculture and Sinking: At a Glance"

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Macroalgal Open-Ocean Mariculture and Sinking: At a Glance

Macroalgae, or seaweeds, are large, plantlike organisms that grow naturally in the ocean and, like land plants, take up and store carbon via photosynthesis. These organisms, which include kelp and rockweed, can transform dissolved CO_2 into biomass at some of highest rates on earth.[22] There are three proposed CDR methods based on cultivation of seaweeds: the deliberate sinking of biomass grown in open-ocean seaweed farms into the deep sea, natural sinking and sequestration, and the deliberate use of seaweed biomass to reduce emissions through technologies or methods other than deliberate sinking.[23] The first pathway, sometimes termed ocean afforestation or macroalgal open-ocean mariculture and sinking, has received the most attention as a CDR method and is the subject of this fact sheet.

Potential Scale of Carbon Storage: Under the most ideal growing conditions, sequestering 0.3 gigatonnes of carbon per year (GtC yr^{-1}) via sinking macroalgal biomass—equivalent to about 22 percent of U.S. CO_2 emissions in 2021—would require new seaweed farms covering an ocean area about the size of Kentucky, roughly 40 times as much area as is currently devoted globally to seaweed farming for all other uses.[24] This would require unprecedented logistics. Any biomass that is sunk to the bottom of the ocean via this method cannot be harvested for other beneficial uses.

Cost: One group of scientists recently estimated that sequestration via sinking of macroalgal biomass could be achieved today for approximately $2,050 per ton C.[25] This is considerably more than the U.S. Department of Energy's long-term cost goal for this CDR pathway of $275 per ton C.[26]

Duration of Carbon Storage: The length of time for which the sunken macroalgal biomass could be sequestered from the atmosphere depends heavily on where in the ocean the sinking takes place. Biomass could be sequestered for more than 500 years if sunk below 1,000 meters in many parts of the ocean, but the timescale would be considerably less if the biomass were sunk in shallower waters.[27]

Technical Readiness: Knowledge borrowed from the existing seaweed farming industry could help advance the technical readiness of macroalgal CDR methods. However, much of the current seaweed farming industry has experience only in inshore and coastal environments; the space in inshore and coastal waters is often already devoted to other marine uses, and these environments are removed from the deep waters where one would need to sink biomass to sequester it for long periods. Farming in the offshore environment has been demonstrated in pilot projects but would be costly and logistically difficult to scale up.[28] Importantly, the sinking of biomass into the deep sea at scales required to achieve gigatonne levels of sequestration has not been demonstrated and remains surrounded by questions of safety, durability, and legality.

Potential Risks and Benefits (Social and Environmental): The effectiveness, scalability, ecological safety, and co-benefits of seaweed-based CDR approaches will depend on many factors, including where the seaweeds are grown and the end use for the plant biomass.[29] Sinking harvested biomass into the deep ocean could lock large amounts of carbon away from the atmosphere for long periods yet rob fragile, slow-growing deep-sea ecosystems of oxygen and increase deep ocean acidity.[30] Cultivated macroalgae canopies could cover large spatial areas and shade local natural primary producers or compete with them for nutrients.[31] Large offshore seaweed farms could also increase the incidence of marine mammal entanglement and compete with other marine spatial uses such as fishing.[32] However, macroalgal aquaculture could create jobs, provide opportunities for co-location with other new, sustainable ocean uses (e.g., renewable energy installations), and create new habitat for a diversity of macroalgae-associated water column species. Some scientists have also argued that seaweed aquaculture could be used to remediate ocean "dead zones," such as in the Gulf of Mexico, by removing excess nutrients that cause these harmful phenomena.[33]

Outstanding Questions: Several aspects of proposed seaweed-based CDR methods are not well understood, including their sequestration potential, the durability of the carbon storage, and how much additional carbon could be stored above the baseline.[34] Verifying the capture and sequestration of CO_2 by macroalgae against the background of natural processes in the ocean remains extraordinarily challenging, from both a technical and a methodological standpoint. For example, due to ocean physics and chemistry, tracking the movement of carbon dioxide from the atmosphere into the ocean and then into the biomass grown in a specific seaweed farm is extremely difficult. Fundamental research is needed in this area to improve carbon accounting. Finally, life-cycle analyses are needed to compare the net CDR benefit of sinking macroalgal biomass against other potential macroalgal CDR pathways such as incorporation into animal feeds or as a substitute for GHG-intensive products such as plastics or fertilizers.[35]

22 Francois Fernand et al., “Offshore Macroalgae Biomass for Bioenergy Production: Environmental Aspects, Technological Achievements and Challenges,” *Renewable and Sustainable Energy Reviews* 75 (August 2017): 35–45, https://www.sciencedirect.com/science/article/abs/pii/S1364032116307018.

23 See Rodney M. Fujita et al., “Carbon Sequestration by Seaweed: Background Paper for the Bezos Earth Fund—EDF Workshop on Seaweed Carbon Sequestration,” Environmental Defense Fund, 2022, https://www.edf.org/sites/default/files/2022-10/Carbon%20Sequestration%20by%20Seaweed.pdf. Natural sequestration is the least certain of these pathways; as seaweeds grow, they shed fronds and release some long-lived dissolved carbon into the deep sea, but these natural losses account for only a fraction of the overall carbon they take up and are hard to measure. If not deliberately sunk to the deep sea, seaweeds can serve as the basis for CDR by being converted into products that could reduce greenhouse gas emissions, either directly (e.g., by addition to feed for cows and other ruminants, which may reduce the production of methane, another highly potent greenhouse gas) or indirectly (e.g., by replacing GHG-intensive products such as fossil fuel–based plastics or fertilizers). Seaweed biomass can also be used as an input for other land-based CDR methods such as bioenergy with carbon capture and storage.

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Ocean Fertilization: At a Glance

Marine plants and algae, like phytoplankton, take up CO_2 during photosynthesis, and this can increase the ocean's uptake of atmospheric CO_2. Ocean fertilization (OF) would use ships to dump specific limiting nutrients into the surface ocean—nitrogen, phosphorus, silica, or, in the most researched example to date, iron—to promote phytoplankton growth through algal blooms. The method assumes that a sufficient quantity of the uneaten phytoplankton from these blooms would then die and sink, transporting carbon into the deep ocean or seafloor sediment for longer-term storage.

Potential Scale of Carbon Storage: Estimates of OF's ability to capture CO_2 vary from less than 1 gigatonne to 5 gigatonnes of carbon per year (GtC yr^{-1}), with 1 GtC yr^{-1} considered most likely.[36] This range in rates stems from different model assumptions about how fast the dead phytoplankton would sink and/or be eaten by predators, nutrient cycling, the specific form of the nutrient that is added, deployment location, and ocean currents.[37] Achieving any significant level of CO_2 capture with OF would require amending vast areas of the ocean (e.g., adding iron to the entire Southern Ocean and the Atlantic, Pacific, and Indian Ocean basins south of 30° S).

Cost: Most fertilization methods are likely to be relatively low in cost, less than $50 per ton of CO_2 captured.[38] Iron-based OF requires the smallest amount of material per ton of CO_2 captured.[39] However, industrial processes that create the fertilizing material can also emit additional CO_2, especially in the case of industrially produced nitrogen fertilizers, making life-cycle greenhouse gas emissions analyses for these processes important.[40]

Duration of Carbon Storage: OF is expected to offer carbon storage on an average of 10 to 100 years, with some carbon being stored beyond 100 years.[41] What happens to the phytoplankton that blooms—whether it is eaten and turned back into CO_2 in the upper water column or in deep water, or it is buried in sediment—heavily affects carbon storage duration for OF methods.[42]

Technical Readiness: OF experiments using iron in the 1990s and 2000s confirmed that fertilization does induce phytoplankton blooms and carbon capture, but scientists found that only some of these blooms led to longer-term carbon storage or atmospheric CO_2 drawdown beyond already naturally occurring processes.[43] New satellite, sensor, and modeling technologies may help reduce uncertainties around the carbon storage capacity of OF.[44]

Potential Risks and Benefits (Social and Environmental): Blooms created by ocean iron fertilization have attracted grazers and predators; some have speculated that enhanced phytoplankton productivity could increase the growth rate of fish populations, such as salmon.[45] Scientists have also speculated that OF could divert nutrients that support phytoplankton growth in other locations ("nutrient robbing") or contribute to harmful algal blooms, water column acidification, or low-oxygen zones.[46] There is no evidence of these consequences from OF field experiments conducted to date, which have been limited in spatial and temporal scales.

Outstanding Questions: The additionality and durability of CO_2 storage from OF are not well known. Verification of CDR via OF is likely to be challenging, especially due to the large areas involved, long supply chains for fertilizing materials, use of seagoing vessels, effects of ocean circulation, and overall biogeochemical complexity of the ocean.[47] Implications of OF for ocean ecosystems are also not well known, and concerns have been raised by the scientific community about harmful algal blooms and phytoplankton community shifts leading to broader ocean ecological changes.[48] There are also significant legal questions surrounding the addition of fertilizing materials to the ocean, which could fall under definitions of ocean dumping.[49]

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Ocean Alkalinity Enhancement: At a Glance

Ocean alkalinity enhancement (OAE), also termed enhanced weathering (EW), aims to alter seawater chemistry, usually by spreading finely ground alkaline minerals like silicates and carbonates in seawater or on coastal lands. (OAE can also be driven by electrochemistry; see related fact sheet). The pulverized minerals dissolve slowly, on the order of years and decades, adding alkalinity to the ocean so that it can absorb additional CO_2 from the atmosphere. This approach dramatically accelerates natural mineral weathering processes, which normally can take thousands of years. This can also decrease ocean acidification.[50] Source materials for OAE—such as lime—would be mined on land or obtained from industrial processes, ground, and then spread on beaches or added to seawater via pipelines or ships.[51] Particles would have to be very small, and locations for mineral addition carefully selected.[52]

Potential Scale of Carbon Storage: Modeling suggests that 75 years of OAE deployed at global scale, affecting most of the surface ocean, would enhance ocean carbon dioxide absorption by 156 gigatonnes of carbon (GtC), an approximate average rate of around 2 gigatonnes of carbon per year (GtC yr^{-1}).[53] This annual uptake is equivalent to about 6 percent of global atmospheric CO_2 emissions from fossil fuel burning in 2018.[54]

Cost: The estimated present cost for OAE with carbonates is about $70 to $120 per tonne of CO_2. At that cost, removing 2 GtC per year via OAE at the scale described above would cost roughly $500 billion to $800 billion per year, or five to eight times all international climate finance funding pledged by parties to the United Nations Framework Convention on Climate Change in 2009.[55] There are currently no detailed cost estimates for global-scale deployment of silicate mineral–based OAE methods.

Duration of Carbon Storage: The length of time that CO_2 could be removed from the atmosphere as a result of OAE is uncertain. It depends on water column physics, chemistry, and biology, but in some cases storage from OAE could last more than a century.[56]

Technical Readiness: The chemistry behind OAE is well established, but the technique poses logistical challenges. Mining, grinding, and transporting enough alkaline material from land to distribute in the marine environment would require massive infrastructure and long supply chains. The energy requirements and CO_2 emissions of OAE operating at full scale are likely to be high, but they are not well researched.[57]

Potential Risks and Benefits (Social and Environmental): Hazards of terrestrial mining are well known; they include harm to local biodiversity and quality of air and water, as well as common social challenges such as safety risks to miners and exposure to pollutants in surrounding communities. Once deployed in the ocean, OAE could increase levels of toxic metals and other minerals or alter the mix of phytoplankton species present, with unknown net effects on biodiversity.[58] However, OAE is expected to help decrease ocean acidification and thereby potentially aid some open-ocean marine life, such as plankton with hard shells.[59] Impacts of coastal alkalinity enhancement (i.e., enhanced weathering) on seashore and nearshore wildlife and vegetation are presently unknown.

Outstanding Questions: It's still unclear whether enough minerals could be prepared for OAE or EW without the serious environmental and social harms associated with most mining activities.[60] The added crushed mineral material itself may carry impurities, such as metallic elements or other minerals that could themselves have environmental impacts. In addition, national and international policies and agreements are not definitive on OAE; most do not comment on it explicitly but do regulate addition of different types of materials and known pollutants to the ocean.[61] As for all marine CDR techniques, verification of these methods would require analysis of total CO_2 emissions associated with building and operating OAE infrastructure and transporting the terrestrially mined materials to appropriate places in the ocean.

50 National Academies of Sciences, Engineering, and Medicine (hereinafter NASEM), *A Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration* (Washington, D.C.: National Academies Press, 2022), https://doi.org/10.17226/26278.

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Electrochemical Ocean-Based CDR Methods: At a Glance

Electricity can be used to remove carbon dioxide from seawater by driving well-understood chemical reactions that either liberate carbon dioxide gas from the seawater for capture and sequestration, or alter seawater's chemical balances to enable it to store more CO_2 than it naturally would.[62] Following these reactions, treated seawater is returned to the ocean, where it will then absorb more carbon dioxide from the atmosphere.[63]

Potential Scale of Carbon Storage: Electrochemical CDR requires large quantities of reactants, seawater, and energy. To remove 0.001 to 0.002 gigatonnes of CO_2 per year (GtC yr^{-1}) electrochemically would require treatment of as much water as currently goes through every desalination plant in the world.[64] Removing just 0.5 (GtC yr^{-1}) per year electrochemically would also require scaling up current worldwide acid production by a factor of about two, or base production by a factor of seven.[65] In terms of energy, removing 1 (GtC yr^{-1}) per year electrochemically would require 2,000 terawatt-hours of electricity per year, or 20 percent of the projected increase in global annual electricity supply by 2040.[66] To contribute to emissions mitigation, electrochemical CDR approaches would have to rely on renewable energy. For some methods, substantial new infrastructure would also be needed to produce and transport reactants or reaction products.

Technical Readiness: Electrochemical CDR has been demonstrated only at prototype scale.[67] There have been no pilot projects or field trials for this technology.[68] The energy needed to pump water and extract carbon dioxide is a significant limitation on electrochemical CDR, but combining this technique with ocean thermal energy conversion, offshore wind facilities, or desalination plants could decrease infrastructure and operating costs.[69]

Potential Risks and Benefits (Social and Environmental): The environmental risks and benefits associated with electrochemical ocean capture of carbon have not been researched.[70] As with existing power and desalination plants, seawater intakes can pose a risk to many marine organisms.[71] Electrochemical CDR techniques would also cause local pH and chemical equilibrium changes to seawater, which could affect marine life and ecology depending on rates, magnitudes, areas, and timescales of change.[72]

Outstanding Questions: Technological developments like improved ion membranes used to help remove CO_2 , corrosion-proof materials, and installations robust enough for the ocean environment will be required to reduce costs for upscaling this technology.[73] Environmental impacts and co-benefits, like the production of hydrogen or chlorine gas during electrochemical ocean capture of carbon, need to be researched.[74] While verification of CDR by direct CO_2 removal from seawater is relatively straightforward, verification by methods that electrochemically alter ocean chemistry (e.g., by creating alkalinity) is likely to be more challenging. As with all marine CDR techniques, verification of these methods would require analysis of total CO_2 emissions associated with building and operating facilities and supplying them with electricity or raw materials.

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Sub-seafloor Geologic Storage of Captured CO_2: At a Glance

Carbon dioxide can be permanently stored under the seabed in geologic reservoirs. This is achieved by injecting captured CO_2 into rock formations thousands of feet beneath the seabed, where it is trapped by a combination of mechanisms such as a caprock with low permeability, capillary or residual trapping, dissolution in brines naturally present in the storage rocks, or reactions that form solid minerals.[75] Stored carbon dioxide may come from carbon dioxide removal (CDR) methods like direct air capture, or possibly even direct ocean capture via electrochemical methods if fully developed (see related fact sheet on electrochemical-based CDR).[76] Carbon dioxide can also be collected using carbon capture and storage techniques, which trap carbon dioxide that would otherwise be emitted from industrial facilities before it enters the atmosphere.[77]

Potential Scale of Carbon Storage: The potential offshore capacity for sub-seabed CO_2 storage is immense. There is capacity for more than 36,000 gigatonnes of carbon dioxide ($GtCO_2$) to be stored offshore under the seabed of U.S. waters alone.[78] The Department of Energy's National Energy Technology Laboratory has estimated that the Gulf of Mexico and Atlantic coastal regions each have the capacity to store on the order of hundreds of billions of tons (many gigatonnes) of carbon dioxide.[79]

Cost: Carbon capture and offshore storage is limited primarily by cost. Transportation of CO_2 offshore is expensive—more costly than onshore geologic injection.[80]

Duration of Carbon Storage: With proper site selection and adequate monitoring for leaks, sub-seafloor geologic carbon dioxide storage has the potential to be extremely durable, offering the longest sequestration timescales of any ocean-based CO_2 storage method. According to the Intergovernmental Panel on Climate Change, injected CO_2 can be safely stored in saline formations for 10,000 years or more with overall leakage rates at less than 0.001 percent per year.[81] Further, in certain types of reservoirs, CO_2 storage is expected to slowly grow more secure over time, as the injected CO_2 dissolves in water or brine or some portion eventually mineralizes into solid form, thereby becoming immobile.[82]

Technical Readiness: Offshore geologic storage has been successfully demonstrated by a handful of small-scale projects, including the Sleipner and Snøhvit projects near Norway, the CarbFix2 project in Iceland, and the Tomakomai demonstration project in Japan.[83] Sleipner and Snøhvit projects stored 0.024 GtC between 1996 and 2019 with no demonstrated leakage.[84] Effective tools for monitoring injected carbon and detecting potential CO_2 leaks from storage have also been developed and demonstrated in the field.[85]

Potential Environmental Risks: Environmental harm could occur from CO_2 leakage during transport or after placement beneath the seabed. Transport and initial injection constitute two risky phases of any geological CO_2 storage projects; the risk is even greater for sub-seabed storage than for terrestrial storage since CO_2 must be transported over or through the ocean by ship or pipeline.[86] A large CO_2 spill or leak could cause temporary but significant ocean acidification, harming a large variety of organisms in the immediate vicinity.[87] Once CO_2 is injected under the seabed, leaks from the storage reservoir could disrupt microbial communities and deep-sea organisms, and these impacts could cascade to larger species and ecosystems.[88] In addition, CO_2 leaked at either stage of the process will ultimately return to the atmosphere, reducing the carbon sequestration benefit of the project.

Outstanding Questions: As mentioned above, sub-seafloor geologic storage of CO_2 has been successfully demonstrated through multiple field and pilot projects.[89] Still, outstanding questions remain around multiple aspects of the approach. Environmental risks associated with transporting and injecting CO_2 offshore require further study. Additionally, research and development is needed for pipeline and platform infrastructure suited to transport and inject CO_2.[90] Congress is supporting research to address these key questions, with recent large-scale investments in CDR and geologic carbon storage through the Infrastructure Investment and Jobs Act (Pub. L. 117-58, 2021) and the Inflation Reduction Act (Pub. L. 117-169, 2022). Further, there are outstanding questions about how the federal government will regulate sub-seafloor geologic storage. Although the Infrastructure Investment and Jobs Act directed the Bureau of Ocean Energy Management to release regulations for carbon sequestration leasing on the Outer Continental Shelf in fall 2022, the bureau has not yet released draft regulations, so the substance of these regulations remains unknown.

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