Storing CO2 in the Ocean: Emerging Technologies, Challenges, and Enabling Factors

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Abstract

The ocean naturally plays a crucial role in mitigating climate change by absorbing approximately 25 percent of anthropogenic CO2 emissions (Le Quéré et al., 2018). In order to achieve the Paris Agreement climate targets, it is increasingly recognized that negative emission technologies (NETs) such as marine carbon dioxide removal (mCDR) will be necessary to complement emissions reduction efforts (IPCC, 2018). mCDR at large scales could significantly help mitigate climate change by capturing anthropogenic carbon dioxide (CO2) and storing it in the ocean for extended periods. This review explores emerging mCDR technologies allowing for long-term (1,000 years+) CO2 storage while considering the safety concerns, efficacy, and environmental impact of these technologies, as well as the enabling factors that are crucial for the growth of a robust mCDR industry.

1. Marine Carbon Dioxide Removal (mCDR) for Long-Term Storage

The Intergovernmental Panel on Climate Change (IPCC) has emphasized the urgency of achieving net-zero greenhouse gas emissions to limit global warming to well below 2°C, ideally 1.5°C, compared to pre-industrial levels, and avoid the catastrophic impacts associated with exceeding this threshold (IPCC, 2021). While significant reductions in emissions are essential, achieving this goal will also likely require the development and deployment of negative emission technologies (NETs) (Fuss et al., 2018). NETs such as mCDR will be necessary to complement emissions reduction efforts (IPCC, 2018).

mCDR technologies leverage the ocean's natural ability to absorb CO2 through physical and biological processes. By deliberately intervening to enhance these processes, mCDR can significantly increase the ocean's capacity to store CO2 for extended periods. The following sections provide an overview of the most advanced mCDR solutions, including geological storage, enhanced ocean natural sequestration, and mineralization and ocean storage.

1.1. Geological mCDR

Geological formations beneath the seabed offer secure, long-term CO2 storage options. Deep saline aquifers (DSAs) are naturally occurring brines with immense storage capacity. When CO2 is injected into DSAs, it reacts with formation water, converting to stable carbonate minerals over geological timescales (Bachu et al., 2008). The Sleipner Project in the North Sea is a successful example of DSA storage, safely sequestering approximately 1 million tons of CO2 per year since 1996 (Bergman et al., 2004). However, careful site selection and monitoring are crucial to prevent leakage and potential disruptions to existing brine ecosystems (Gustafsson et al., 2017).

Another geological storage option is the repurposing of depleted oil and gas reservoirs. These subsurface cavities can leverage existing infrastructure for CO2 storage (Beaumont et al., 2011). However, ensuring the long-term integrity of these formations requires careful evaluation of potential leakage pathways through abandoned wells or fractures (Liu et al., 2018).

1.2. Enhanced Ocean Natural Sequestration (EONS)

Enhanced Ocean Natural Sequestration (EONS) aims to enhance the ocean's natural CO2 uptake processes in various ways. Ocean fertilization is an EONS solution that involves adding iron or other nutrients to stimulate phytoplankton growth, which increases biological CO2 sequestration in the form of sinking organic matter (Aumont et al., 2006). However, large-scale iron fertilization experiments have shown that while phytoplankton growth is stimulated, most of the additional biomass is consumed by zooplankton and respired back to CO2, limiting the amount of carbon sequestered in the deep ocean (Aumont et al., 2006; Duarte et al., 2009). Furthermore, concerns regarding unintended ecological consequences, such as disrupting food webs and oxygen depletion in deep waters, have limited the application of ocean fertilization (Duarte et al., 2009).

Artificial upwelling is another EONS solution that involves pumping deep, nutrient-rich ocean water to the surface, stimulating phytoplankton growth and CO2 absorption through photosynthesis (Law et al., 2008; Breuer et al., 2017). However, unless clean energy is used, the energy required to pump large volumes of deep water to the surface may offset the CO2 sequestration benefits (Rau et al., 2013). Additionally, concerns surrounding the potential disruption of bottom-dwelling ecosystems remain to be addressed (Rau et al., 2013).

1.3 Mineralization and Ocean Storage

Emerging technologies that utilize mineral reactions to directly sequester CO2 in the ocean show promise. Direct ocean CO2 capture and mineralization involves capturing CO2 from industrial emissions or the atmosphere, dissolving it in seawater, and reacting it with alkaline materials like calcium or magnesium hydroxide to form stable carbonate minerals (Khoo et al., 2008; Rau et al., 2013). These minerals can then be stored on land or deployed in the ocean. However, the energy required for mineral production and the potential impacts of large-scale deployment need further investigation (Wang et al., 2015).

Another approach is ocean CO2 hydrate formation, which involves injecting CO2 into deep ocean waters to form stable clathrates (hydrates) under specific pressure and temperature conditions (Li et al., 2016). While this method has the potential for long-term CO2 storage, the long-term stability of the hydrates and potential ecological disruptions require further evaluation (Jang et al., 2015).

2. Towards Acidification-Neutral CO2 Storage Technologies

While the ocean's vast capacity for CO2 storage is compelling, the direct absorption of CO2 leads to ocean acidification, which can have detrimental effects on marine ecosystems (Duarte et al., 2013). The development of technologies that aim to store CO2 in the ocean without exacerbating acidification will therefore be a crucial factor for the growth of a robust mCDR industry.

Traditional ocean carbon storage solutions, such as direct injection of captured CO2 into deep ocean depths, raise concerns about potential leakage, environmental impacts on deep-sea ecosystems, and ethical considerations (Caldeira et al., 2005; Buckley et al., 2010; National Academies of Sciences, Engineering, and Medicine, 2019). Furthermore, injecting pure CO2 directly acidifies the surrounding water, contributing to the broader acidification issue (Kellner et al., 2019).

Electrochemical approaches offer a promising solution to this problem. Ebb Carbon's technology electrochemically removes acidity from seawater before exposing it to CO2, promoting its conversion to bicarbonate, a stable and natural carbon storage form in the ocean (Khatiwala et al., 2020). Similarly, marine electrolyzers use electrolysis to extract hydrogen from seawater, releasing hydroxide ions that neutralize acidity. The remaining CO2-enriched brine can be stored underground or reused in chemical processes (Lu et al., 2020).

Enhanced natural processes, such as ocean afforestation and mineral weathering, also show potential for acidification-neutral CO2 storage. Ocean afforestation involves kelp farming and controlled cultivation to harness the natural CO2 absorption capacity of macroalgae while creating economic opportunities and restoring marine ecosystems (Chung et al., 2017). Mineral weathering involves spreading crushed silicate minerals like olivine on land or directly in the ocean to accelerate natural weathering processes that absorb CO2 and neutralize acidity (Renforth et al., 2021). However, careful monitoring and management are crucial to ensure the sustainability of these approaches and to mitigate potential side effects on marine life (Kerrison et al., 2018; National Academies of Sciences, Engineering, and Medicine, 2019).

Carbon mineralization involves reacting captured CO2 with minerals like magnesium hydroxide to form stable carbonates, mimicking natural rock weathering processes (Sanna et al., 2014). Further research is needed to optimize these technologies, ensure long-term stability, and understand potential environmental consequences (Gerdemann et al., 2007; Power et al., 2013; Sanna et al., 2014; Gadikota & Park, 2015; Kelemen et al., 2019).

3. Measurement, Reporting, and Validation (MRV) Technologies as Crucial Enablers of mCDR

The development of a robust mCDR industry heavily relies on the establishment of effective measurement, reporting, and validation (MRV) technologies (ARPA-E, 2023). These technologies must accurately quantify the amount of carbon dioxide removed from the atmosphere, determine the longevity of the storage, and provide reliable estimates of the uncertainties associated with these measurements. High-quality MRV data is crucial for carbon markets to assess the value of carbon credits and for financial institutions to evaluate investment risks in mCDR projects (ARPA-E, 2023).

To achieve these goals, a significant shift in the approach to collecting chemical oceanographic data is necessary. Traditional single-point data collection methods must be replaced by persistent, large-scale sensing of relevant parameters across vast areas and volumes of the ocean. ARPA-E (2023) has identified several key advancements in technology that could rapidly enable effective MRV and establish a strong financial value for the mCDR industry. These advancements include the development of sensors capable of volumetric or area-wise quantification of oceanographic properties, precision, and accuracy comparable to current state-of-the-art sensing approaches, integration with existing ocean data collection platforms, and extended deployment periods without human intervention. Interdisciplinary collaboration between sensor developers, oceanographic scientists, modelers, and the carbon market industry will be crucial to develop viable and scalable MRV technologies for mCDR, ensuring that the data collected is relevant and useful for carbon credit valuation and risk assessment (ARPA-E, 2023).

4. Conclusions and Recommendations

mCDR holds promise as a tool for mitigating climate change, and the current state of the art requires more research and development for its large-scale deployment.

Improving the efficiency and reducing the energy demands of capture and mineralization processes are crucial for the feasibility and cost-effectiveness of mCDR technologies. Additionally, robust environmental monitoring programs are essential to ensure long-term storage security, identify and mitigate potential ecological impacts, and refine existing models.

While promising approaches exist for CO2 storage technologies that do not exacerbate ocean acidification, further research and development are needed to ensure technical feasibility, scalability, cost-effectiveness, and potential unforeseen environmental consequences. Addressing these challenges will make it possible to harness the immense potential of the ocean to mitigate climate change.

The development and deployment of advanced measurement, reporting, and validation (MRV) technologies will be crucial for the success of the mCDR industry, as these technologies provide the necessary data to quantify the effectiveness of mCDR projects, assess their long-term viability, and enable the accurate valuation of carbon credits. To ensure the successful development and implementation of MRV technologies, it is recommended that government agencies take the lead in fostering interdisciplinary collaborations by establishing research programs and funding opportunities that bring together sensor developers, oceanographic scientists, modelers, and the carbon market industry to create robust, scalable, and financially viable MRV solutions that meet the needs of all stakeholders involved in the mCDR sector.

mCDR technologies cannot be viewed as a substitute for emissions reduction. Instead, they should be considered part of a comprehensive climate strategy alongside rapid decarbonization efforts. While this review of mCDR technologies pointed out further research and development needs, the looming climate crisis and the short timelines left for humanity to limit global warming to well below 2°C do not leave us with a lot of time to develop and deploy large scale mCDR solutions. Therefore, difficult choices will have to be made in relation to what costs, including environmental costs, can be accepted for CO2 removal and storage to reach the scale required for the necessary climate change mitigation.

5. References

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