Direct Ocean Capture vs. Ocean Alkalinity Enhancement for Scalable Ocean Carbon Dioxide Removal

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Abstract. This paper explores various ocean-based negative emission technologies (ONETs) for carbon dioxide removal: direct ocean capture (DOC) using bipolar membrane electrodialysis (BPMED) and hollow fiber membrane contactors (HFMCs); ocean alkalinity enhancement (OAE) using olivine addition and BPMED alkaline stream return. In DOC, BPMED separates seawater into acidified and basified streams to concentrate CO_2, while HFMC removes CO_2 from the acidified stream. For OAE, traditional mineral addition methods using olivine increase seawater alkalinity through natural mineral weathering, while electrochemical BPMED allows controlled alkalinity manipulation. For comparative purposes, key performance vectors, including energy consumption, cost, geographical locality, scalability, and environmental impacts, were evaluated. Results indicate that DOC has more potential in integration with renewable energy, while OAE is fitted for larger-scale deployment. Both technologies present environmental considerations, such as concerns with drastic ocean chemistry changes and possible environmental and social impacts from mineral additions. To advise future research and pilot-scale implementation, DOC and OAE together highlight complementary pathways for ONETs, offering insights into technical feasibility, cost-effectiveness, environmental trade-offs, and potential integration with renewable energy.

Keywords: Bipolar membrane electrodialysis (BPMED); carbon dioxide removal (CDR); direct ocean capture (DOC); ocean alkalinity enhancement (OAE); ocean-based negative emission technology (ONET).

1. Introduction

Ever since the first anthropogenic CO_2 was generated from fossil fuels, humans have continuously released a substantial amount of CO_2 into the atmosphere. The UN Environment Programme (UNEP) called upon all nation-states to accelerate low-carbon development to keep the global temperature rise below the 1.5°C threshold [1], as recommended at the 2015 Paris Agreement on climate change [2-4]. To mitigate excess emissions, the capture of over 10 gigatons of greenhouse gases, primarily carbon dioxide, is essential [5]. Approximately 20-40% of anthropogenic CO_2 was absorbed by the ocean, making it a crucial carbon sink. Despite covering 70% of the Earth's surface, this thermodynamically favorable process cannot offset all anthropogenic CO_2 emissions [6]. This process has decreased the surface-ocean pH from 8.2 to 8.1 and lowered the carbonate mineral saturation state [7]. Thus, the removal of CO_2 from seawater becomes increasingly crucial for indirectly capturing atmospheric CO_2. Carbon dioxide removal (CDR) technologies target green transformation by removing and permanently storing CO_2 from the environment, thus generating negative emissions [8].

Ocean-based Negative Emission Technologies (ONETs) is a notable set of CDR technologies aimed at increasing ocean CO_2 uptake and retention [8]. Some of the most well-known ONETs include biological concepts such as microalgae cultivation, macroalgae cultivation, and marine habitat restoration. In addition to biological concepts, two promising engineered ONETs, direct ocean capture (DOC) and ocean alkalinity enhancement (OAE), have emerged as novel technologies in the development stage for future large-scale implementation [9]. Therefore, it is important to identify recent and latent technologies within each approach for a comprehensive understanding of the deployment potential. The objective of this paper is to present current advances in DOC and OAE approaches, highlighting the technical mechanisms, pros and cons, as well as specific energy consumption. The review builds on a comparative analysis of potential direct and indirect, intentional and unintentional impacts based on key performance vectors and presents potential synergies for scalable implementation in the marine environment.

2. Background of Ocean-based Negative Emission Technologies (ONETs)

Prior to the development of DOC and OAE technologies, it is important to have a thorough understanding of ocean chemistry. As mentioned in Section 1, the ocean pH has decreased by 0.1 units due to the uptake of anthropogenic CO_2, resulting in ocean acidification. Ocean chemistry comes into play as the carbonate system facilitates CO_2 exchange between the atmosphere and seawater. When CO_2 gas dissolves into seawater, it forms carbonic acid (H_2CO_3), which equilibrates with bicarbonate (HCO_3^-) and carbonate ions (CO_3^{2-}) [8]. This works as a buffer system responsible for maintaining ocean pH below a depth of 100 m. There are two types of equilibrium systems involved between the CO_2 in the atmosphere and the ocean system. Through Henry's Law, the equilibrium between atmospheric CO_2 and gaseous CO_2 is regulated, while once dissolved, CO_2 dissociates twice into bicarbonate and carbonate ions [10]. Together, the properties of the described systems control ocean chemistry and are employed in DOC and OAE technologies.

Current ONETs involve diverse approaches to enhance the natural carbon sequestration capacity of the ocean, broadly categorized into 8 types [10]. Physicochemical methods like DOC and OAE alter seawater chemistry to boost CO_2 intake. Ocean fertilization stimulates phytoplankton growth to increase biological carbon sequestration, while ocean upwelling and downwelling physically pump nutrient-rich or carbon-saturated waters to promote long-term sequestration. Biological solutions involve protecting and restoring mangroves, macroalgae, and other blue carbon ecosystems that store carbon in biomass and sediments. Biomass-based strategies convert marine biomass for biochar or bioenergy with CO_2 capture and storage and terrestrial biomass dumping into the deep ocean [11]. While a variety of ONETs have been proposed, DOC and OAE technologies represent two of the most actively researched and scalable approaches.

3. Direct Ocean Capture (DOC)

Engineered removal of CO_2 by DOC directly removes dissolved inorganic carbon (DIC) (i.e., carbonic acid, bicarbonates, and carbonate) from seawater. This system benefits from the fact that atmospheric CO_2 is already absorbed by the ocean, thus primarily involving its extraction (desorption) step [12, 13]. DOC consists of two main pathways: the acidification route and the alkalinization route, mainly implemented via electrochemical approaches including electrochemical cation/anion exchange membrane (CEM/EHL) systems and other membrane contactor designs [8]. Among these various methods, bipolar membrane electrodialysis (BPMED) and hollow fiber membrane contactors (HFMC) stick out as the most operationally mature technologies that represent the critical stages of electrochemical separation of seawater and extraction from acidified streams. In the alkalinization pathway, BPMED produces a basified stream that is returned to the ocean to enhance atmospheric CO_2 uptake, while for the acidification pathway, technologies like HFMCs acidify the seawater, releasing the dissolved CO_2 for storage. Both technologies ultimately remove CO_2 either as a gas or as carbonate minerals, where the treated seawater gets discharged back into the ocean for alkalization [8].

3.1. Bipolar Membrane Electrodialysis (BPMED)

The basis of DIC removal from seawater could be performed through BPMED, where seawater is pumped through an electrochemical BPMED system that uses a pH-swing concept. The swing electrochemically shifts the pH of a working fluid, which results in two output streams: acidified and basified seawater [14]. Eisaman et al. was the first reported design for electrodialysis used in CO_2 capture from the ocean. In this design, a nine-cell prototype was employed using a bipolar membrane (BPM) with an anion exchange membrane (AEM) and a cation exchange membrane (CEM) to convert seawater into two streams, one with high and one with low pH. Inside the BPM, water dissociates where the ion-selective membranes transport the H^+ and OH^- ions in opposite directions. AEMs and CEMs transport counterions to maintain charge balance while keeping the electrodes' compartments separated [15]. The system achieved a 59% extraction of dissolved inorganic carbon (DIC) as gaseous CO_2 with an electrochemical energy consumption of 5.5 GJ/tonne CO_2 (242 kJ/mol CO_2). However, this design experiences voltage losses and higher electrochemical energy consumption for CO_2 removal due to the generation of hydrogen and oxygen at different electrodes [8, 15].

An improved BPMED system in overcoming these challenges has been proposed by Digdaya et al. (2020), replacing the hydrogen and oxygen evolution reactions (water splitting) occurring on typical electrodes with the reversible redox couple, potassium ferro/ferricyanide ($K_3/K_4[Fe(CN)_6]$) [16]. Figure 1a presents the schematic design of such a unit, while figure 1b shows the overall experimental setup for the CO_2 capture. This system reached 71% capture efficiency of DIC and reduced the electrochemical energy consumption to 3.4 GJ/ton CO_2 (151 kJ/mol CO_2) [8, 16]. Compared to the method proposed by Eisaman et al. (2012), this improved system has a 20% increase in efficiency and a 38% reduction in energy demand [8].

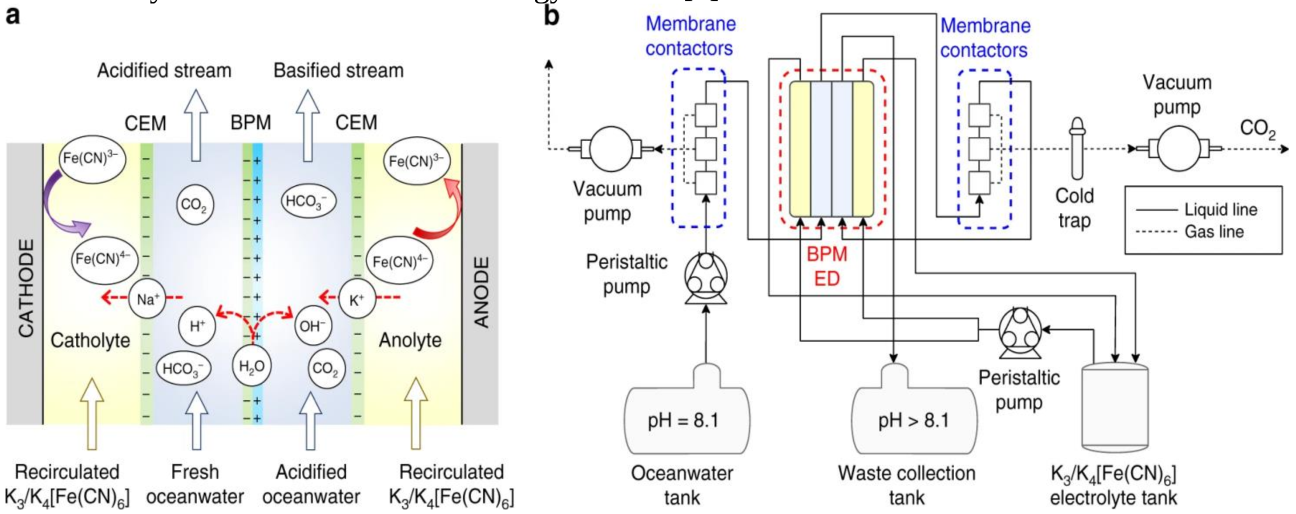

Fig. 1 a) Schematic design of the improved BPMED unit. b) Process flow diagram of the experimental setup for CO_2 capture from seawater [16].

3.2. Hollow Fiber Membrane Contactors (HFMCs)

In addition to BPMED, hollow fiber membrane contactors (HFMCs) were used by Kim et al. (2023) to present a novel membrane-less asymmetric electrochemical seawater capture system. Unlike BPMED, this system uses chloride-mediated electrochemical pH swing without the costly bipolar membranes. In one cell, protons were released to acidify the seawater (stream), freeing the CO_2 from bicarbonate/carbonate species, which get stripped under vacuum using HFMC. The second cell then reverses the process, re-alkalinizing and consuming the proton before the stream is returned to the ocean, generating electrodes by recapturing chloride ions [17]. This system reached a low energy consumption of 122 kJ/mol CO_2 with high faradic efficiency, where most of the electricity supplied was used productively for the intended reaction. However, there are drawbacks due to silver electrode degradation during the regeneration process, which could increase maintenance costs and reduce the long-term stability of the system, as shown in figure 2 [18].

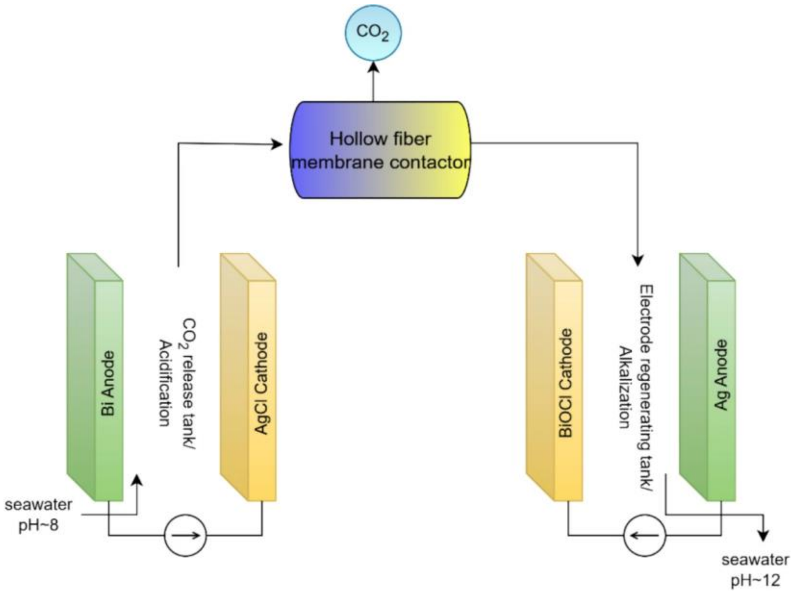

Fig. 2 Principle of chloride-mediated electrochemical pH swing system for CO_2 removal from seawater [6].

4. Ocean Alkalinity Enhancement (OAE)

Intentional manipulation of ocean alkalinity was first proposed in 1995, inspired by Earth's modulation of alkalinity on geological timescales [19]. OAE technologies accelerate the conversion of CO_2 into bicarbonate and carbonate by adding alkalinity as aqueous hydroxides or solid minerals such as silicate or carbonate minerals. While natural atmospheric equilibrium takes weeks to months to complete, this process rapidly reduces local CO_2. Among various methods, mineral addition of olivine and electrochemical alkalinity generation using BPMED were selected. Olivine is among the most abundant minerals, representing a traditional OAE approach and a scalable way to enhance seawater alkalinity. While electrochemical production of alkalinity using BPMED offers the most efficient way to produce alkaline species. Compared to mineral addition, BPMED allows a controlled source of alkalinity from brine, producing NaOH with minimal gas byproducts, whereas solid minerals dissolve more slowly [20].

4.1. Silicate Minerals and Rocks

Silicate minerals like olivine are preferred as an OAE method due to their weathering process, which naturally consumes CO_2 and increases ocean alkalinity. To accelerate this process, silicate minerals are crushed and pulverized into small particles, increasing the surface area, and dispersed into the ocean to enhance dissolution. Olivine, one of the most abundant silicate minerals, exists as forsterite (Mg_2SiO_4) and fayalite (Fe_2SiO_4) [19]. Its weathering in seawater produces bicarbonate ions and dissolved silica, storing CO_2 in the ocean for long periods:

$$(Mg, Fe)_2SiO_4 + 4CO_2 + 4H_2O \rightarrow 2(Mg^{2+} / Fe^{2+}) + 4HCO_3^- + H_4SiO_4. \quad (1)$$

However, variations of this reaction occur in environments where carbonate precipitation can take place, producing solid $CaCO_3$ or $MgCO_3$. These secondary precipitates reduce the efficiency as they release CO_2 back into the ocean:

$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O. \quad (2)$$

In response, coastal enhanced weathering (CEW) offers a solution to the slow dissolution of olivine. Coastal zones, where waves and tides resuspend particles, increase surface contact. CEW uses larger particles (>63 μm) applied to coastal waters, reducing the energy requirement and excess CO_2 emissions for grinding [8].

4.2. Bipolar Membrane Electrodialysis (BPMED) Alkaline Stream Return

Unlike common OAE approaches that add alkaline minerals, electrochemical approaches using electrodialysis generate alkalinity that is returned to the ocean. The electrodialytic generation of alkalinity uses aqueous (NaCl) brine from seawater or desalination plants, providing ions and conductivity. Like DOC, this system uses a three-chamber BPMED known as a triplet, consisting of BPM, AEM, and CEM. BPM produces hydroxide and protons from the dissociation of water, where, under an applied electric potential, Na^+ moves toward OH^- to form NaOH, while Cl^- moves toward H^+ to form HCl [20]. This process generates one alkaline and one acidic stream, without significant gas production, and maintains efficiency due to its batch/closed-loop configuration. Brine, water, and the electrode rinse solution recirculate until the desired NaOH solution is achieved. The resulting NaOH (alkaline stream) is then directly added to the ocean, a step unique to OAE, whereas the alkaline stream in DOC is primarily used to neutralize processed seawater before discharge. An advantage of aqueous hydroxides is that the rate at which the alkalinity is added to the ocean is equal to the rate that is delivered [20]. Nevertheless, the process still needs to be monitored carefully to control the pH and dilution to prevent the precipitation of $Mg(OH)_2$ (can result in an undesired increase in turbidity) or $CaCO_3$ (can reduce the efficiency of OAE for CO_2 removal) within the mixing zone.

5. Comparative Assessment of DOC and OAE Technologies

Table 1. Assessment of Key Performance Vectors Between DOC and OAE

Criteria	Direct Ocean Capture (DOC)	Ocean Alkalinity Enhancement (OAE)
Energy Consumption	Energy consumption of 2.4–5.5 GJ/ton of CO_2 [10]. Electrochemically mediated carbon capture devices can combine renewable energy to generate power for CO_2 capture.	For one OAE design, the estimated energy cost is 5.7–8.2 GJ with a land requirement of 7.1–13.1 m² per ton of CO_2 captured and stored [21].
Cost	Stand-alone, electrodialysis-based DOC plant estimates 1,870–2,500 US$/ton CO_2; could be reduced to 500 US$/ton CO_2 if a desalination plant is in close vicinity but will also reduce CO_2 capture capacity to <100 kton/year of CO_2 [17]. Estimated capital and operating costs for an HFMC plant that captures 980,000 tons/year of CO_2 were US$9,565/ton of CO_2 [18].	Implementation in high-energy environments allows more cost-effective mineral deployment due to extensive water mass movements (i.e., surf zones). Grain sizes can be larger (mm range) compared to continental shelves (μm-range) mineral size [20]. Consistent with other OAE methods, ocean liming requires <6,485 GJ/ton of CO_2 removed and costs $70-160/ton of CO_2. Integration of biomass and hydrogen energy vectors may improve carbon balance and cost feasibility [20].
Land Use & Geographical Locality	Operational plants can be deployed offshore, avoiding the use of valuable space and reducing costs and logistics related to transportation and storage sites [17].	Logistically challenging at a large scale. Requires massive mining and transportation efforts. The form of alkalinity/material used is also an issue.
Efficacy & Scalability	Captura, a carbon removal company, launched the first DOC pilot plant off the coast of Newport Beach, CA, in 2021. As of February 2025, Captura has announced the start of operations of its latest DOC pilot plant in Hawaii, capable of capturing 1,000 tons of CO_2 annually [22].	Vesta, a public benefit organization that seeks to implement OAE through coastal carbon capture. In July 2022, Vesta deployed 500 cu yd of olivine sand along the coast of Southampton, NY, for sea waves to erode the olivine mineral [23]. Since 2023, Ebb Carbon, a marine carbon dioxide removal (mCDR) tech company, has been operating a 100-ton/year mCDR system using OAE bipolar electrodialysis [24].
Environmental & Social Risks	Electrochemical processes may generate trace metals from electrodes. Acidified streams need to be treated to avoid potential environmental contamination [19].	Requires expansion of mining operations, comparable to the global cement industry (~7 Gt rock/year) [20]. Environmental impacts: pollution, habitat loss, and erosion; release of heavy metals may be toxic to marine organisms at high concentrations. Social impacts: demographic shifts, infrastructure pressures, impacts on indigenous communities, and worker health risks.

There are certain mechanistic similarities between direct ocean capture (DOC) approaches and those discussed in ocean alkalinity enhancement (OAE) approaches. As stated in sections 3 and 4, electrochemical DOC methods aim to directly remove DIC through alkalinity cycling from the seawater, while electrochemical OAE methods aim to increase the net alkalinity to enhance the long-term capacity to absorb atmospheric CO_2 of the ocean [8].

Both DOC and OAE employ membranes to aid in electrochemical separation, like the implementation of bipolar membrane electrodialysis (BPMED). In this system, cation- and anion-exchange membranes with a central bipolar membrane allow precise control of pH by splitting water into H^+ and OH^- ions. Similarly, when BPMED is applied to an aqueous chloride brine solution, it generates two primary products: a basified stream rich in NaOH and an acidified stream rich in HCl. In addition, two secondary products are formed as hydrogen gas and oxygen gas [9].

Although these products are generated in both DOC and OAE systems, there are differences in their use of the primary products. When using BPMED in DOC, the acidified stream is introduced to lower the pH of a separate ocean water stream, shifting the equilibria and converting DIC into CO_2 gas, which is then captured via vacuum stripping or membrane contactors (i.e., HFMC) [9]. After the CO_2 removal, the basified stream is returned to restore the pH, maintaining ocean chemistry. In OAE, the basified stream is reintroduced to the ocean, increasing alkalinity and enhancing CO_2 uptake, while the acidified stream is removed for terrestrial applications such as neutralizing alkaline waste in mine sites.

Aside from mechanistic similarities and differences, estimated cost, together with the associated environmental and social impacts, plays a vital role in assessing scalability. For future deployment, costs are expressed in US dollars per metric ton of CO_2 removed (low: <\$50/t CO_2; medium: ~\$100/t CO_2; high: >>\$150/t CO_2), along with confidence levels (low, medium, high) [19]. DOC presents a high cost (>\$150/t CO_2). As shown in Table 1, an electrodialysis-based DOC plant estimates 1,870–2,500 US\$/ton CO_2 [17]. Even with improved siting like co-location with desalination plants, the cost remains around \$500/ton CO_2 [17]. By contrast, OAE, especially traditional methods like mineral addition, is more cost-effective due to reliance on natural water movement. The natural grinding mechanism enables the use of larger grain sizes, thereby reducing costs, with estimates of \$70-160/ton of CO_2 [20]. Further integration with biomass and hydrogen energy systems could improve both carbon balance and cost feasibility. However, the nature of mineral addition requires substantial mining operations, which may offset the cost-effectiveness of the mechanism. In terms of scalability, both approaches show medium to high potential for removal of >0.1–1.0 Gt CO_2/yr (medium confidence). Notably, OAE may reach >1 Gt CO_2/yr if applied globally [19].

6. Prospects

The application of both DOC and OAE for increasing ocean CO_2 uptake and retention holds significant potential but depends on various factors, including efficiency, scalability, environmental impact, and more, as shown in section 5. With the emergence of electrochemical membranes as a capture solution for DOC technologies, the prospects for this system are characterized by its precise CO_2 removal and modular, controllable design. Pilot projects such as Captura's 1,000 t/year facility in Hawaii present its technical feasibility [22]. Moreover, potential integration with renewable energy can power BPMED units, minimizing CO_2 emissions associated with energy use. When implementing OAE using minerals like olivine, precise control of quantity and distribution is essential to minimize effects on the ecosystem. Large deposits of mineral particles have the risk of benthic smothering, altering microbial communities, and affecting mineral dissolution rates. To minimize these risks, the use of sprinkler systems as a dispersed application is preferred. For silicate minerals like olivine, potential side effects include the release of heavy metals (e.g., Ni), which could pose ecological risks at high concentrations, so laboratory testing and mesocosm experiments are recommended before large-scale implementation [20].

Together, DOC and OAE work toward complementary goals, providing both large-scale CO_2 sequestration through OAE while allowing for precise, targeted CO_2 removal in DOC. The combination of both strategies could enable a flexible carbon removal pathway, optimized for site-specific conditions and localized environmental monitoring. To explore the feasibility of deploying large-scale facilities, a proper understanding of process economics, safety risks, and environmental effects of DOC and OAE is of great importance. For example, the use of minerals and power for DOC and OAE could potentially limit the development of these strategies. Therefore, to address these shortcomings, it is recommended to perform a techno-economic analysis (TEA) with a life cycle assessment (LCA) to identify the potential environmental risks and the influencing parameters for a more comprehensive evaluation [17].

7. Conclusion

This review paper investigated two novel ocean-based negative emission technologies (ONETs): direct ocean capture (DOC) and ocean alkalinity enhancement (OAE). Through an extensive analysis of existing research, each technology presents evident advantages and challenges, offering promising approaches for carbon capture and storage.

DOC technologies focus on an electrochemical pathway that shows the potential of integration with renewable energy in the future and is less constrained by land use. Captured CO_2 can be stored offshore, reducing transportation and storage demands. Compared to traditional OAE, DOC is more energy efficient. However, with current estimates ranging from US$1,870 to 2,500 per ton of CO_2 for stand-alone electrodialysis plants, global-scale implementation remains a challenge. Although costs may fall to ~$500 per ton when coupled with desalination, this comes at the expense of reduced capture capacity.

OAE, by contrast, offers the potential of low cost due to the simplified process in grain size if deployed in high-energy environments (i.e., surf zones), and integration with biomass or hydrogen energy vectors could enhance both its carbon balance and economic feasibility. However, the scalability of OAE remains limited by the enormous mining operations required, which introduce substantial environmental and social risks.

The future of optimization of both technologies for enhanced efficiency and cost-effectiveness could focus on hybrid strategies through technological refinement (introducing renewable energy in process-engineered techniques) for DOC and scaling up sustainable sourcing to address OAE’s mining challenges. Furthermore, to ensure a sustainable and effective deployment in combating climate change, continued monitoring and assessment of environmental implications alongside techno-economic analysis (TEA) and life cycle assessments (LCA) are essential.

References

[1] United Nations Environment Programme. Emissions gap report 2023: Broken record – Temperatures hit new highs, yet world fails to cut emissions (again). 2023-11-20. Accessed 2025-09-01. https://www.unep.org/resources/emissions-gap-report-2023

[2] Nuala Burnett, Tamsin Edwards. COP28: The 2023 United Nations Climate Change Conference. 2023-11-10. Accessed 2025-09-01. https://commonslibrary.parliament.uk/research-briefings/cbp-9884/

[3] Intergovernmental Panel on Climate Change. Sections. In: Climate Change 2023: Synthesis report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. 2023-03-20. Accessed 2025-09-01. https://doi.org/10.59327/IPCC/AR6-9789291691647

[4] United Nations Framework Convention on Climate Change. Technical dialogue of the first global stocktake – Synthesis report by the co-facilitators on the technical dialogue. 2023-09-08. Accessed 2025-09-01. https://unfccc.int/documents/631600

[5] Austin Reed Lieber, Marina Hildebrandt, Shanna-Leigh Davidson, et al. Demonstration of direct ocean carbon capture using encapsulated solvents. Chemical Engineering Journal, 2023, 470(1): 144140.

[6] Mehar U. Nisa, Haris Ishaq, Curran Crawford. Electrochemical approaches for CO2 point source, direct air, and seawater capture: Identifying opportunities and synergies. Environmental Science and Pollution Research, 2025.

[7] Richard E. Zeebe. History of seawater carbonate chemistry, atmospheric CO2, and ocean acidification. Annual Review of Earth and Planetary Sciences, 2012, 40(1): 141–165.

[8] Sumudu Karunarathne, Sara Andrenacci, Andres Carranza-Abaid, et al. Review on CO2 removal from ocean with an emphasis on direct ocean capture (DOC) technologies. Separation and Purification Technology, 2025, 353(1): 128598.

[9] Austin Reed Lieber. Multiphysics investigations of emerging direct air and ocean carbon capture technologies, University of Pittsburgh, 2024.

[10] Chameera Jayarathna, Michel Maelum, Sumudu Karunarathne, et al. Review on direct ocean capture (DOC) technologies. Social Science Research Network, 2022.

[11] Lina Röschel, Barbara Neumann. Ocean-based negative emissions technologies: A governance framework review. Frontiers in Marine Science, 2023, 10.

[12] Zhuo Li, Xianrui Qin, Yajun Li, et al. A mini-review for direct air capture (DAC) and direct ocean capture (DOC) using electrochemical technologies. Future Batteries, 2025, 5(1): 100020.

[13] Prince Aleta, Abdelrahman Refaie, Mohsen Afshari, et al. Direct ocean capture: The emergence of electrochemical processes for oceanic carbon removal. Energy & Environmental Science, 2023, 16(11): 4944–4967.

[14] Rezvan Sharifian, Martijn R. Wagterveld, Ibadillah A. Digdaya, et al. Electrochemical carbon dioxide capture to close the carbon cycle. Energy & Environmental Science, 2021, 14(2): 781–814.

[15] Matthew D. Eisaman, Keshav Parajuly, Alexander Tuganov, et al. CO2 extraction from seawater using bipolar membrane electrodialysis. Energy & Environmental Science, 2012, 5(6): 7346–7352.

[16] Ibadillah A. Digdaya, Ian Sullivan, Meng Lin, et al. A direct coupled electrochemical system for capture and conversion of CO2 from oceanwater. Nature Communications, 2020, 11(1): 4412.

[17] Omnya Al Yafiee, Fatima Mumtaz, Priyanka Kumari, et al. Direct air capture (DAC) vs. direct ocean capture (DOC)–A perspective on scale-up demonstrations and environmental relevance to sustain decarbonization. Chemical Engineering Journal, 2024, 497(1): 154421.

[18] Seoni Kim, Michael P. Nitzsche, Simon B. Rufer, et al. Asymmetric chloride-mediated electrochemical process for CO2 removal from oceanwater. Energy & Environmental Science, 2023, 16(5): 2030–2044.

[19] The National Academies Press. A research strategy for ocean-based carbon dioxide removal and sequestration. 2022.

[20] Matthew D. Eisaman, Sonja Geilert, Phil Renforth, et al. Assessing technical aspects of ocean alkalinity enhancement approaches. State of the Planet, 2023, 2-oae2023: 1–29.

[21] Lei Xing, Huw Pullin, Liam Bullock, et al. Potential of enhanced weathering of calcite in packed bubble columns with seawater for carbon dioxide removal. Chemical Engineering Journal, 2022, 431(1): 134096.

[22] Tara Bojdak. Captura opens new direct ocean capture pilot plant in Hawaii. 2025-02-06. Accessed 2025-09-01. https://capturacorp.com/captura-opens-new-direct-ocean-capture-pilot-plant-in-hawaii/

[23] Vesta. Vesta annual monitoring report: coastal carbon capture at North Sea Beach (June 2022–January 2023). 2023-01-24. Accessed 2025-09-01. https://www.vesta.earth/field-pilots

[24] Ben Tarbell. Full steam ahead: Ebb's ocean carbon removal solution is up and running at PNNL-Sequim. 2023-08-21. Accessed 2025-09-01. https://www.ebbcarbon.com/post/ebb-carbon-ocean-carbon-removal-solution-operational-at-pnnl-sequim