A Critical Analysis of the Ocean Effects of Carbon Dioxide Removal via Direct Air and Ocean Capture – Is it a Safe and Sustainable Solution?

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THE OCEAN FOUNDATION

Acronyms

IPCC	Intergovernmental Panel on Climate Change
GHG	Greenhouse Gas
CDR	Carbon Dioxide Removal
NET	Negative Emission Technologies
BECCS	Bioenergy with Carbon Capture and Storage
PSC	Point Source Capture
DAC	Direct Air Capture
DOC	Direct Ocean Capture
IEA	International Energy Agency
FUTURE Act	Furthering carbon capture, Utilization, Technology, Underground storage, and Reduced Emission Act
45Q	A performance-based U.S. tax credit incentivizing carbon capture and sequestration or utilization
BPMED	Bipolar Membrane Electrodialysis

Executive Summary

Catalyzed by the 2015 Paris Agreement, there are numerous initiatives for policies and science-based solutions to reduce greenhouse gas emissions and to achieve net-zero emissions internationally. President Biden plans to achieve net-zero in the United States no later than 2050. Despite forward-moving initiatives, the Intergovernmental Panel on Climate Change (IPCC) recently reported that two-thirds of the countries that have pledged to reduce greenhouse gas emissions have committed to levels that remain insufficient in meeting vital international climate targets [1].

The overarching goal to reduce greenhouse gas (GHG) emissions must be accomplished by transitioning to a more equitable and environmentally just energy system that reduces pollution while meeting global food, transportation, and energy needs. Carbon dioxide removal (CDR) is at the forefront of policy change, investments, and technology to reduce the amount of CO_2 in the atmosphere and the ocean. We must respond quickly, yet carefully, to the considerable pressure to remove carbon dioxide from the atmosphere even as we transition away from burning fossil fuels and other anthropogenic CO_2-emitting activities.

There are a number of emerging technologies based on direct air capture (DAC) and direct ocean capture (DOC) which use machines to extract CO_2 directly from the atmosphere or the ocean and move the CO_2 underground to storage facilities or utilize the CO_2 to enhance oil recovery from commercially-depleted wells. These technological interventions are in contrast to nature-based solutions. These include restoring mangroves and other coastal and marine ecosystems, regenerative agriculture, and reforestation to remove and store carbon dioxide in plants and soils. These nature-based strategies can offer multiple community benefits, biodiversity benefits, and long-term carbon storage, a global benefit.

This report mainly focuses on the viability and consequences, including potential harm to the environment and livelihoods of the direct air capture and direct ocean capture approaches.

Section I: Capturing Carbon dioxide from the Air

A. Introduction

Carbon is an integral part of the Earth's atmosphere. The carbon cycle encompasses an exchange between the ocean, soil, rocks, and the biosphere. Nearly all terrestrial and marine organisms depend on photosynthesis involving a sufficient amount of carbon compounds. CO_2 emits infrared radiation and plays an essential role in the greenhouse gas effect causing a warming in Earth's atmosphere. As of 2019, the average monthly level of CO_2 in the atmosphere exceeded 413 parts per million.

Increased production of fossil fuels, urban development, and monoculture agriculture decreases carbon storage and sinks and increases the release of excess carbon into the atmosphere. The ocean has absorbed about 30 percent of the CO_2 emitted since the beginning of the industrial revolution. The CO_2 dissolves in the ocean, leading to a decline in the overall pH level of the ocean [2] (ocean acidification). This trend, coupled with warming and deepening seas, threatens marine biodiversity and the capacity of the ocean to perform the ecosystem services on which all life depends.

The 2018 IPCC Special Report recognized that the majority of modeled pathways to mitigate climate change incorporate CDR and carbon storage. However, the IPCC also expressed concern that many models relied very heavily on CDR despite the significant uncertainties regarding the feasibility, harm to livelihoods and scalability. Currently, a number of negative emission technologies (NET) are being developed and deployed to capture CO_2 from the air [3].

For example:

- Afforestation: creating a forest or woodland, usually monoculture to convert carbon dioxide to oxygen through photosynthesis
- Bioenergy with carbon capture and storage (BECCS): extracting carbon from biomass and producing heat, electricity, or fuels
- Point source capture (PSC): capturing CO_2 directly from power plants and factories before it escapes into the atmosphere
- Ocean fertilization: adding nutrients (usually iron) to the upper ocean to stimulate plankton blooms and remove carbon dioxide
- Biochar: a charcoal that is produced by pyrolysis of biomass and used as a soil amendment for both carbon sequestration and soil health
- Direct air capture (DAC): process of directly capturing CO_2 from ambient air
- Direct ocean capture (DOC): direct capture of CO_2 in the ocean
- Improved land use practices to effect soil carbon sinks: Agroforestry, cover crops, intercropping, organic agriculture, and/or regenerative agriculture
- Seagrass meadow, salt marsh, mangrove, and other ecosystem restoration: transplanting and/or repairing different ecosystems in the sea and in coastal regions

Many of the carbon storage technologies under development are costly, ineffective and/or induce environmental and economic injustice. For example, PSC would only decrease emissions associated with the fossil fuel industry and not fully remove them. Furthermore, PSC could increase GHG emissions, if the captured CO_2 is used to increase the production of oil or coalbed methane. Although the technology is evolving for shipping, PSC cannot remove emissions from other industries such as aviation, cement production, and large-scale animal agriculture. BECCS and afforestation require vast amounts of land, and may, to be effective, require more acreage than is currently categorized as marginal or low productivity. Therefore, use of productive land for BECCS operations may further threaten biodiversity, water and food security [3]. Ocean fertilization presents problems (from sourcing the iron to transporting the iron to in-ocean impacts) that generate significant environmental, social, and economic harm.

Direct carbon capture could cut a company or government's emissions to zero when the limits of emissions reductions are reached. In theory, carbon removal technology would help offset emissions or even make its impact negative, by taking more CO_2 out of the air than a specific industry or activity produces. Direct CO_2 removal is receiving considerable attention and financial investment from Bill Gates and Elon Musk, among others. Direct air capture requires considerable energy for both the capture and storage of CO_2. The land footprint is considered to be relatively small (not including the storage) and it could be powered by renewable energy such as solar, wind, and geothermal [4].

The CO_2 once captured can be compressed into a liquid state and transported by pipeline, ship or road tanker to be pumped underground and stored in a depleted oil and gas reservoir or coal bed. Presently, the primary commercial use of the carbon captured is for enhanced oil recovery resulting in the production of transport fuels such as diesel. The CO_2 could also be stored in deep geological formations in the ocean, the sea floor or directly in the water column of the ocean. The captured carbon could be used in other applications, including microalgae cultivation and production of carbonated beverages, agriculture, plastics, fiber and synthetic fuel. The market for these options is currently rather small. The consequences and climate footprint of such uses must be carefully calculated so that they do not present a false solution to the challenge of excess CO_2 in our atmosphere.

As societies move forward to mitigate climate change, it is vital to do so ethically, through helping vulnerable communities and protecting wildlife and ecosystems. This means that strategies such as DAC and DOC must be safe, carbon negative, regulated, and equitable in their design, location, and operation. The environmental consequences should be investigated extensively from the manufacture of the equipment through to the disposal and long-term storage of the CO_2.

B. DAC Technologies

Capture: There are multiple technologies that fall into the category of DAC. All require considerable energy to remove carbon dioxide from the air. CO_2 is more dilute in the ambient air than in emissions from a smokestack, power station, or a cement plant. Therefore, more energy and electricity are needed to capture the CO_2, possibly promoting fossil fuel use as a consequence.

Proponents argue that DAC plants could be powered by renewable energy, nuclear energy, or use abandoned or retired mines as a plant location site. However, the immense amount of renewable energy required for operating DAC plants could be alternatively used in the renewable energy sector itself to reduce the fossil fuel industry. DAC plants require a limited amount of water and land and could eliminate a need for long distance CO_2 transport [4]. DAC is structured using modular design; therefore, it could be scaled up in the future. However, the amount of land required for storage, transport and pipelines, and the likelihood of a carbon neutral market for carbon products should be deliberated.

There are two different types of DAC currently being implemented, solid direct and liquid direct. Liquid direct requires high temperature heated air to pass through a chemical solution that removes the carbon in liquid state and returns the rest to the air. Most liquid direct capture models currently are designed to use fossil fuels to achieve heating to higher temperatures [3]. Solid direct requires a filter that absorbs the CO_2 in a solid state when heated at a lower temperature than liquid direct. The low temperature, solid capture is preferable, as it has potential for extensive cost reduction through utilization of waste heat from other sources, a high modularity, and no demand for external water [3]. Additionally, heat pumps could be fully operated by renewables and a moderate climate is recommended for operation as it requires a heating and cooling process.

Currently, there are 15 Direct Air Capture plants in operation worldwide, mainly in Europe and North America.

For example:

1. Icelandic company CarbFix's [5] current technology captures the carbon emissions as they are released from an adjacent geothermal plant and combines the CO_2 with geothermal fluid (water), then injects it into the ground where it turns into stone in less than two years.[1] Swiss company Climeworks is partnering with CarbFix at the same site to store the carbon captured from the air by its machines. When the Climeworks installation is complete in May, the paired technology is expected to remove 4000 tons of carbon dioxide per year.
2. Climeworks Swiss plant captures CO_2 from ambient air powered by a geothermal plant. The plant is capable of capturing 1,000 metric tons of CO_2 a year. Climeworks uses this captured carbon in greenhouses for agriculture production which can enhance crop yields by 20 percent [6].
3. The first large-scale direct air capture plant should be functioning in the United States by 2023, capable of capturing one million t CO_2/year [4]. This plant is being built in the Permian Basin by Occidental Petroleum and their partners. The captured CO_2 will be ultimately used in enhanced oil recovery, which is the extraction of oil from a retired oil field. Retrieving up to 60% of a reservoir's oil that would not be possible with primary and secondary oil recovery. During this process, the CO_2 should be injected permanently into the reservoir. However, this would only partially counteract the CO_2 emissions from the burning of the oil being produced which would exceed the amount of CO_2 being captured.

Disposal/Storage of Captured Carbon: The energy cost depends on the choice of solid or liquid capture and whether the captured carbon is being used in a product, as fuel, or stored underground. Storage of carbon underground requires a compressor, high pressure, and trapping mechanisms [7]. Currently, 80% of the CO_2 captured is being used for enhanced oil recovery. The CO_2 can be stored in terrestrial and marine saline aquifers, mineral basalt, and depleted oil and gas reservoirs [8].

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[1] This process relies on basalts, where the carbonated water reacts with elements such as calcium, magnesium and iron, forming carbonates that fill up empty spaces in the rocks underground, accelerating a natural process that can take centuries.

Terrestrial saline aquifers consist of an injection of CO_2 to depths of 500m to 3000m. They are usually made up of sedimentary rock and covered by a layer of impermeable rock. The CO_2 is less dense than the brine in terrestrial injection, therefore some CO_2 will rise up. The theory is that the CO_2 will be trapped in the impermeable rock. Seabed saline aquifers involve CO_2 injection at depths greater than 2700 m below the ocean's surface. The CO_2 is buried under low-permeability sedimentary rocks. The CO_2 is denser than seawater at this pressurized depth resulting in less leakage [8].

Mineral basalt storage is an in-situ sequestration process, which highly pressurizes CO_2 and pumps it deep underground into basaltic rock, which is rich in mineral silicates that reacts thermodynamically with CO_2 to form mineral carbonates or bicarbonates. Oil and gas reservoir storage consists of storing CO_2 in retired fossil fuel reservoirs that have a layer of impermeable rock above a layer of permeable rock theoretically forming a trap for the stored CO_2 [8].

Additionally, storage of CO_2 is also possible on the ocean sea floor and directly into the sea. However, the legal status of storing carbon in the ocean is unknown and further research is needed to analyze the different environmental consequences on various locations in the ocean water column. For example, in shallow sub-seabed, disposal of carbon dioxide combined with the conditions of the seabed and the sediment are not suitable. The formation of the CO_2 hydrate would be in a gaseous or liquid state that is more buoyant than water resulting in leakage [9].

Figure 1 is a detailed map showing different possibilities for DAC plant locations in the United States, encompassing the variables of storage underground, tax credits, transportation, financial costs, re-use options, and low-carbon energy sources. Scaling up requires better mapping of the sources and sinks, storage sites, and monitoring [10]. Figure 1 is one illustration of how the number of DAC operations could be increased.

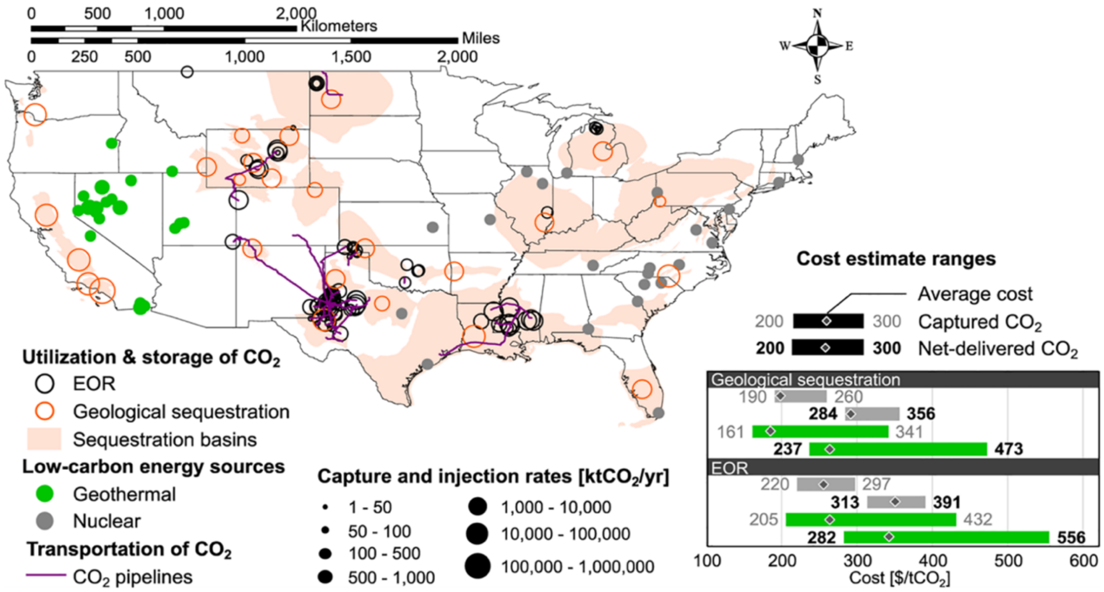


Figure 3. Geographical distribution of the proposed scenarios along with the estimated ranges of the costs. The map shows the distributed geological sequestration (open orange circles) and EOR (open black circles) opportunities with DAC plant possibilities based upon the scenarios of using available thermal energy sourced from geothermal (closed green circles) and nuclear (closed gray circles) for opportunities qualifying for 45Q tax credit (100 $ktCO_2$/yr or greater). The cost figure shows the projected costs per tonne of CO_2 delivered for DAC paired with reliable storage and reuse (EOR). Included is the capital, operating, and maintenance expenditures for capture, separation, compression, and transport for all scenarios, plus injection in the nearest storage basin for the geological sequestration option and less tax credits for qualifying facilities as described under 45Q.

Figure 1: Geographical representation of DAC plants [7]

C. Viability

Supporters believe that DAC technology has the potential to remove greenhouse gas emissions significantly over the next ten years. Current projections conclude that carbon captured by DAC could increase 10-fold by 2030 [4]. However, the rate of this increase would require an immense amount of energy to operate, possibly from the fossil fuel industry. Additionally, the impact these plants actually make towards reducing the CO_2 from the atmosphere should be analyzed at world-scale. Careful environmental and economic assessments of all elements of DAC activities need to be undertaken to determine its true greenhouse gas footprint and climate sustainability.

If this were to be a viable tool to support a transition to a cleaner economy, considerable investment would need to be made immediately and accelerate rapidly in order to reduce costs and support meeting the Paris Agreement goals for reducing CO_2 in the atmosphere and the ocean [3]. A competitive analysis should be performed for this same investment to be made in nature-based carbon removal solutions. An important question to consider, are the costs and efficiency of DAC really comparable to the long-term benefits of restoring habitats and enhancing ecosystems?

Economics: For DAC to be successful in helping to achieve net-zero emissions, large-scale operations are preferable. However, these plants are very expensive to operate with considerable operational and transportation costs for every ton of carbon removed. To fully deploy, DAC technology could represent as much as ¼ of all energy use by 2100 [11]. Additionally, storing the CO_2 varies on price, based on the technology and energy needed. Those costs include the location of the plant, which energy source is being used, technology type, and labor required. Transport of the CO_2 to be re-used in products, agriculture, or synthetic fuel could be costly as well. The pipelines used for the transport of CO_2 could pose significant environmental and health risks for the communities and ecosystems. DAC does provide carbon technical and engineering jobs, but labor is a relatively small part of the overall cost. Figure 2 is a detailed example of the estimate of different costs, equipment, and labor needed for operating a DAC plant that has a capacity of capturing 100 kt-CO_2/year from the air.

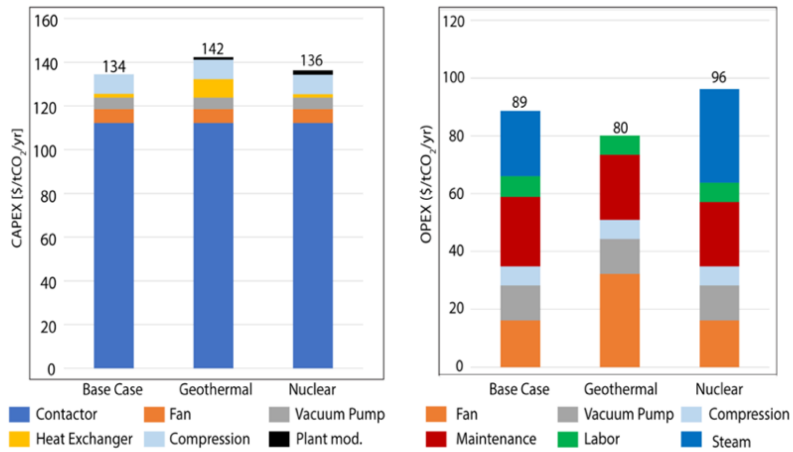


Figure 1. Breakdown of annualized capital cost (left) and annual operating and maintenance costs (right) per tonne of CO_2. Costs are calculated for a system capable of processing 100 ktCO_2 per year.

Figure 2: Breakdown of estimated financial cost of a DAC plant [7]

The Market: There is currently no marketplace vast enough to support innovators to investigate different types of machinery and other technologies to reduce the cost. One reason that the market is trivial is the complex physical properties of CO_2 resulting in a limited utility in most existing commercial products. The cost of carbon offsets for the Climeworks DAC is $1200 or more per ton, versus the CarbFix point source capture is closer to $25 per ton, while the EU rate is set at $48 per ton. Climeworks has a number of major corporate purchasers of its offsets, who see it as an investment in a technology-based solution. For example, Bill Gates has invested in the current technology by purchasing Climeworks' capacity at a "bulk rate" of $600 per ton. Opportunity costs should be considered, a detailed comparison to nature-based CDR is recommended to compare offsets such as, reforestation or blue carbon costs.

Large-scale costs are currently unknown and likely variable. An International Energy Agency analysis suggests that without scale, DAC is not enough of a solution, but if it is going to be a tool in the toolbox, then considerable investment is going to be needed [4]. In the near term, international cooperation, government investments, carbon taxes, public procurement of offsets, capital investments, and other state or federal tax incentives are needed if the strategy is to be implemented at scale [12]. At global commercial-scale, the IEA cites industry estimates that the levelized cost ranges from 94 to 232 $/t-$CO_2$ [13]. However, it is likely that such estimates do not consider any potential environmental compliance or liability, nor harm to biodiversity, communities and indigenous populations. Likewise, there is an expectation that government subsidies will be considerable, and the market will continuously expand. Such subsidies should be weighed against the value of public and private investments in proven nature-based carbon reduction solutions that can be readily scaled up to benefit indigenous peoples and coastal communities, as well as aquatic biodiversity.

US Tax Code Subsidies:

The FUTURE Act passed in 2019, which is "Furthering carbon capture, Utilization, Technology, Underground storage, and Reduced Emission." Congressional support from the FUTURE Act allows for doubling tax credits for capturing and permanently storing CO_2 in geological formations, using it for enhanced oil recovery, and/or producing products such as cement, chemicals, plastics or synthetic fuels. The act provides a $35 tax credit per ton of CO_2 via direct capture [6].

The recently enacted 45Q tax credit for power plants and industrial facilities is a performance-based tax credit incentivizing carbon capture and sequestration or utilization. Currently, DAC can qualify for 45Q tax credit if the plant removes more than 100kt CO_2/yr. However, under current law, these facilities must commence construction by 2024 to qualify for the tax credit, and should include geological storage or a beneficial reuse of the CO_2 [7].

In the long-term, direct carbon capture requires additional tax subsidies that are comparable to those enjoyed by the fossil fuel industry to be economically viable. However, those subsidies enable the fossil fuel industry to externalize harm to communities, biodiversity, and to planetary health, and should not accrue the same problems to DAC technologies. Deployment opportunities could be closely linked to vigorous CO_2 pricing devices and accounting frameworks that acknowledge the value of negative emissions connected with the CO_2 captured [4]. To be truly sustainable, the tax scheme must also internalize the costs to the environment of energy use for capture and transport and the social consequences of both operations.

D. Consequences

Currently, DAC is costly and technology-intensive, and the plants and products are uncertain in future price and productivity. There are many different ways to deploy DAC technology and the captured CO_2, leading to ambiguities about the true costs that should be analyzed by scientists and engineers and regulated by polices that consider environmental consequences and environmental justice. Fundamentally, a comprehensive "cradle to grave" analysis of DAC technology and operations must be undertaken to fully understand its effects from manufacture to CO_2 disposal or usage. These analyses must consider all of the effects on nature, nearby communities, and on the biodiversity of the land and sea—weighing the amount of CO_2 removed from the air when operational against any harm and potential harm. The effects of CO_2 leakage from the storage sites into aquatic ecosystems must also be evaluated. Only then could adequate regulatory frameworks be drafted and liability established. Decisions could then be made about the true viability of DAC as a climate change mitigation strategy. The immediate areas of potential concern include the following.

Manufacture, operation and location of facilities: DAC causes environmental harm from extraction, refining, transport, and waste of the minerals used for capture [6]. Overall, if DAC plants do not use recycled materials for the infrastructure, the carbon footprint is much higher [14]. Utilizing retired oil reservoirs to establish storage facilities and fuel the operations by burning oil promotes using fossil fuels and can result in increased GHG emissions. The location should also consider the land utilized, permeability of land, nearby air and noise pollution, and the discharge into local waterways.

Entrainment, heat islands, and toxic releases: To date, the potential impact of DAC plants on birds, insects, and other wildlife has been minimally studied, if at all. Given the global concern about drastic declines in populations of birds and insects alike, such studies should be undertaken at all existing DAC plants, and be integral to the approval of new ones. These studies should be in addition to the life-cycle cost analysis of the plants already discussed.

Use of CO_2 captured: Given the regulations and incentives currently in place, DAC encourages the use of fossil fuels for operation. Using the captured carbon dioxide for plastic production, for example, would lead to more plastic in the environment, because currently less than 10 percent of plastic is recycled. This plastic would generate additional CO_2, methane and other GHG emissions through incineration or the breakdown of plastics in the environment overtime. Using the captured carbon for production of synthetic fuels results in more CO_2 emissions into the atmosphere as well. However, renewable-based energy system integration of DAC is expected to be superior to BECCS and usage of fossil fuels [3]. Coupling with nuclear energy could result in environmental and health consequences from radioactive waste storage, including cancer risks [4]. Currently, DAC emissions are most negative coupled with wind power as an electricity source and permanently storing the carbon [14].

Disposal of CO_2 captured: Storing the carbon underground could induce seismic activity, including tremors and small earthquakes. Furthermore, leakage underground could lead to tainted waterways and leakage into the air would contribute to higher CO_2 levels in the air [15].

There are different trapping mechanisms that could be deployed. One is solubility trapping, which is dissolution of CO_2 into the salt water. Second is residual gas trapping consisting of immobilization by capillary forces in the post injection period and mineralization through geochemical interactions between the CO2, brine, and rock [7]. However, large areas of permeable rock are needed, and continuous monitoring is recommended to avoid leakage into groundwater and the air. Furthermore, trapping mechanisms and storing carbon deeper underground is more costly and time consuming.

Offsetting of Risk: An analysis and comparison of the different social, environmental and economic costs to other negative emissions technologies (NET) should be investigated. DAC has potentially significant negative consequences depending on the usage, placement, and energy source. Therefore, careful research and planning should be performed prior to commercial implementation which should address potential failure as well as operational effects. The regulatory framework should be designed to minimize harm to biodiversity and human communities and provide for enforcement and reparations. Enforcement mechanisms could include such measures as requiring posting of bonds to pay for harm due to system failure or negligent actions given that these are new technologies and their life cycle is not fully tested.

E. Effects on the Ocean

Costs: The cost of ocean carbon storage based on the cost of offshore pipelines, ships and energy costs is estimated at 6 to 31$/t$CO_2$ net injected [16]. There is a high cost involved in minimizing leakage because as noted before, storage should be drilled at least 2700 meters below the sea floor. CO_2 liquid is saturated and negatively buoyant at this depth, compared to sea water [17]. However, a comprehensive cost analysis is recommended and should be performed in detail.

Storage under the seafloor: The drilling of CO_2 into the ocean floor results in an alteration of pressure and temperature that could cause the CO_2 to move towards the ocean surface [9]. CO_2 leakage into the ocean from underground storage could cause a drop in the pH of the coast and the ocean locally with negative effects on nearby ecosystems. Continuous leakage, especially from multiple facilities, could lower the background pH of the ocean with cascading negative effects on ocean biodiversity and could even reduce the capacity of the ocean to absorb additional emissions. The outflow of CO_2 would cause a change and unequal distribution of pH, which could add to the current acidity of the ocean resulting in health and environmental consequences for marine life and plants. Leakage of CO_2 into the sea could cause respiratory stress and reproduction effects for marine life, is lethal for coastal fauna, and produces metabolic repression or torpor even at low CO_2 levels [17]. Additionally, research is not yet clear regarding the CO_2 tolerance of coastal species and deep-sea species.

Discharging CO_2 in the ocean: Direct disposal of CO_2 in the ocean would result in a surplus of phytoplankton growth which could uptake CO_2 at a higher rate but could also result in an excess amount of phytoplankton disturbing the food chain and functioning of marine ecosystems [17]. Additionally, all of the consequences listed above would be amplified, meaning this option to store CO_2 requires attention legally and environmentally as the process results in many unknown and known environmental destructions to the vital ocean and marine life.

Ocean Rebound: The amount of CO_2 in the world is in a dynamic and constantly shifting equilibrium between the biosphere, ocean, and the atmosphere. This equilibrium is why the ocean absorbs a significant proportion of anthropogenic CO_2 emissions each year, reducing the amount remaining in the atmosphere [18]. If DAC and other large-scale technologies are used to turn global emissions net-negative, then that equilibrium could also go into reverse. Thus, it is possible that the CO_2 removed using DAC or other mechanical negative emissions technologies at high enough scale could be offset by the ocean releasing CO_2 back into the atmosphere, reducing their supposed efficacy [11].

Section II: Capturing Carbon from the Water Column of the Ocean

A. Introduction

The ocean absorbs 30 percent of the carbon dioxide that is released into the atmosphere. The carbon dioxide dissolves in water and creates carbonic acid that releases hydrogen ions to bind and form bicarbonate. This bicarbonate will not escape the ocean simply. Over time, the CO_2 slowly enters the deep ocean and deposits and mixes with the bottom ocean layer [19]. The absorption of a third of all emissions since the onset of the industrial revolution has affected the basic pH in the ocean. The ocean is becoming more acidic, which in turn affects the marine food chain. Coupled with the destruction of habitats and animals from carbon storage, ocean acidification also adversely affects the capacity of the ocean to absorb additional carbon. Increasing the capability of the ocean to store carbon is one option to mitigate climate change. Restoring and enhancing this capacity could be done in different ways biologically, chemically, and technologically.

Biologically: Approximately 30 percent of seagrass meadows are gone worldwide, likewise an estimated 35 percent of coastal marshes have disappeared, and 35 percent of mangrove forests. Storage and sequestration through restoration of coastal and nearshore ecosystems and ocean biomass is a viable option. Seagrasses are capable of carbon sequestration at scale that also delivers diverse carbon sinks, reduces pollution, and decreases degradation [20]. Seagrass and coastal ecosystem restoration have immense benefits for marine ecosystems, tsunamis and sea level rise protection, filtering pollution, and providing jobs for local communities. Furthermore, carbon is stored in living animals such as fish, shellfish, and whales. Therefore, restoring these species to their full abundance and providing suitable habitats in the ocean is vital.

Chemically: Adding alkalinity as dissolved solid minerals results in an increase of pH and catalyzes carbon uptake by the ocean and could slow down ocean acidification—although this is a largely untested at scale. Ocean alkalinization directly affects shallow and coastal waters the most environmentally [21]. Iron fertilization involves transporting iron filings (generally toxic mine tailings) to dump in distant parts of the ocean to create the conditions for extreme phytoplankton blooms, which then die and sink to store carbon at the bottom of the ocean. Iron fertilization is currently banned worldwide but remains attractive to those who believe that carbon removal is fundamental regardless of the consequences or its carbon footprint.

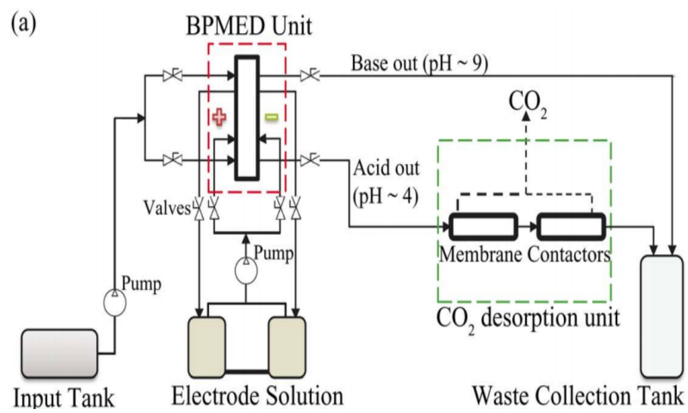
Mechanically: Direct carbon capture by removing carbon dioxide straight from seawater is a technology that is in its infancy. Seawater electrodialysis uses electricity to accelerate chemical reactions that store CO_2 in the seawater [22]. This approach runs electric currents through the seawater. This technology could extract up to 60 percent of the total dissolved inorganic carbon from seawater as a gas. Direct capture of CO_2 in the ocean requires an electric power supply, pump and filter. Currently, the process is costly and very time consuming with a slow extraction rate [23].

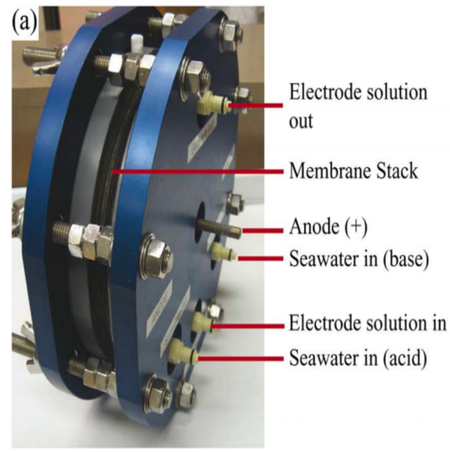
The focus of this section is on the technology of direct carbon capture from the ocean (DOC), its viability, and the possible environmental consequences of implementing this strategy at scale.

B. Direct Carbon Capture from the Ocean

Capture: Currently, there are two types of electrodialysis designs for CO_2 capture from oceanwater [23]. In general, the objective is to drive the CO_2/bicarbonate balance towards dissolved CO_2 by acidifying the seawater. A liquid-gas membrane contactor captures the gaseous CO_2 [23]. This process would require electro-chemical acidification cells with major components including electrode compartments, a cathode and an anode, and a cation-permeable membrane [24].

Another method that is more efficient and novel is to directly extract CO_2 from the ocean using a bipolar membrane electrodialysis (BPMED) unit and a vapor-fed CO_2 reduction cell. This method results in an acidified solution and basified solution that could be combined into a neutral-pH solution [23]. A detailed scheme and example of this unit is provided in figures 3 & 4.





Figures 3 & 4: Schematic setup of BPMED operation and a detailed picture of the BPMED unit [23]

Disposal/Storage: The first method results in CO_2 that would be stored in tanks and then pumped under the seafloor to more than 2700m to limit leaking. The BPMED extraction method results in a neutral pH-solution, that in theory could be released back into the ocean with minimal harm to marine life. However, there should be an extensive environmental analysis of the effects of such releases on the water column and the ecosystems in the ocean.

C. Technological Viability

Energy Efficiency: In seawater, CO_2 degassing at a pH below 6 is dependent on temperature, carbonate, and salinity concentration [24]. The combination of BPMED and a CO_2 reduction cell results in a total Faradaic efficiency of up to 95% for an electro-chemical CO_2 reduction to CO [23]. Faradaic efficiency is the productivity rate of electrons being transferred in an electrochemical reaction, therefore, 95% is quite efficient for CO_2 removal. An ocean carbon capture plant is favorable for energy efficiency over direct air capture with a total estimated energy use of 1.3 $kWhkg^{-1}$ (Watt Hour per Kilogram) of CO_2 compared to a range of 1.54 to 2.45 $kWhkg^{-1}$of CO_2 in the atmosphere [23]. Combined with offshore wind and wave power as energy sources could reduce the overall energy costs of direct carbon removal in the oceans. Comparison to the impact of directly using offshore wind and wave power as a renewable energy source should be considered.

International legal frameworks must be in place before this technology is fully deployed at scale [22]. These frameworks should detail site regulations and carbon disposal methods, and include measures to assure full accountability for compliance. Other risks to their operations should be considered, including hurricane and tsunami damage to DOC plants. Locating CO_2 removal devices throughout the ocean column should be investigated as well to see if harm from surface storms or to the neuston can be mitigated. Further novel research and technology advances need to be fully tested to increase efficiency, lower the environmental consequences and costs of direct capture of CO_2 in the ocean in order to assess this technology for use at scale internationally.

D. Economic Viability

Currently, this process of direct carbon capture is expensive. The technology would need to be improved to increase the capacity of direct CO_2 capture in the ocean. Current estimated costs of a stand-alone system for direct capture in the ocean and storage is \$1.87- \$2.05 kg^{-1} CO_2 [23]. Co-location with a desalination plant by utilizing the infrastructure can reduce costs to about \$0.5 kg^{-1} CO_2 but the amount of CO_2 captured would be less than 100 kt-CO_2 $year^{-1}$ and there are significant brine disposal issues associated with de-sal operations. Nevertheless, the costs are barely researched and are debatable for large-scale deployment [23]. Life-cycle carbon, labor, maintenance, location, and appropriate waste disposal costs should all be considered in a further economic analysis.

The value of other NET for the ocean should be considered as well. Coastal ecosystems have been degraded worldwide due to coastal overdevelopment, excess nutrient runoff, industrialization of coastal and nearshore waters, among other causes. With the loss of those ecosystems, there is an accompanying loss of filtration, storm resilience, and other ecosystem services. Restoration of kelp forests, seagrass, mangroves and saltwater marshes at scale increases the capacity of the ocean to store carbon in the plants and soils of these ecosystems.

Seagrass transplantation has a median cost of 32,348 USD/ha and mangrove restoration has a median cost of 5,571 USD/ha [20]. As an example, the cost per ton of planting seagrass for carbon sequestration is about \$20/ton of carbon removed. A direct comparison of costs is recommended to fully comprehend the full costs of ecosystem restoration versus direct carbon capture in the ocean. Seagrass meadows and mangroves are important carbon sinks and vital habitats for an array of sea life. Additionally, these restoration activities offer a diverse range of jobs with varying skill levels to design the projects and grow the plants. Afterwards, the restored ecosystems improve food security and storm resilience, and can increase economic opportunity through activities such as eco-tourism, small scale fisheries, and managed recreational fishing.

In theory, further scientific research and pensive policies could result in direct ocean capture having a significant impact on reducing CO_2 emissions and could offer one approach to removing anthropogenic gas from the environment [24]. However, on balance, mechanical direct carbon capture from the ocean may be too cost-prohibitive economically, socially, and environmentally.

E. Consequences for the Ocean & Coastal Communities

Coastal Communities: Approaches to removing carbon from the ocean must consider the potential effects on ocean biodiversity, ocean and coastal ecosystems, and coastal communities, including indigenous peoples. Potentially positive effects of appropriate local and skill-level employment generated from the projects should be considered, especially those that outlast the construction phase. There should be a unified community understanding and acceptance of pilot testing and impacts on the coastal communities' health and economics as a pre-condition of implementing at a large-scale [22]. Likewise, there should be an enforceable commitment—through bonds or other means—from the private or public entity establishing the project to address environmental and other harms from its construction and operation.

Ocean and marine life: Currently, ocean carbon removal equipment adds an industrial use to the ocean, and has the potential to increase ocean noise pollution, disrupt the benthic community, entrain ocean plants and animals, and pollute the water with high concentrations of chlorine and CO_2. Presently, the lack of investigation, policies, and improvement in technology is restrictive to progressing in an efficient and timely manner. This technology could result in significant seawater discharge, including surplus free chlorine in the seawater. The effect of this chemical change on marine life is not understood and should be further investigated. Additionally, this process can impact the pH, especially in the colder months and outside the tropic zones, as the temperature and salinity are lower [24]. The byproduct of direct carbon capture would reduce the pH in the ocean locally. This could increase ocean acidification, which would negatively affect the strength of shells for some marine life and the life cycles of fish species. Furthermore, a focus on investigating the capture of CO_2 at different depths of the water column is needed as these contain distinctive consequences to various ecosystems within the ocean.

Section III: Conclusion

No carbon removal technology is a substitute for drastically reducing greenhouse gas emissions from the transportation, energy, and agriculture sector (among others). As with all new technology, these carbon capture technologies receive tremendous attention because of their perceived potential to accomplish societal goals without making choices that are too challenging politically. However, if we do not weigh the full life cycle costs of that technology from manufacture to implementation to disposal, including the environmental, social, and economic costs, then we cannot assess whether the new technology provides a net benefit to our earth and to society. Even if carbon dioxide removal (CDR) direct capture from the air or ocean is technically feasible, we do not know enough about the unintended consequences and costs. It is possible that when all costs are factored in, these technologies would have a limited application and value in our overarching suite of tools to achieve a net-zero CO_2 emissions world.

Even as the ocean has taken up roughly a third of GHG emissions since the onset of the Industrial Age, human activities have destroyed huge swaths of coastal and ocean ecosystems and greatly reduced abundance of marine fauna, which has reduced the ocean's ability to further support carbon storage and other services. Yet, restoring marine ecosystems such as kelp forests, mangroves, seagrass meadows and saltwater marshes has multiple ancillary benefits beyond carbon storage, including improving food security for human and dependent species, water quality, and coastal resilience. Given these attributes and the significantly lower cost per ton of carbon removal via restoration, any technological fixes must truly be a win-win.

A. Recommendations

1. Assess, using a full cradle-to-grave approach, the environmental and economic costs of direct air capture (DAC) machinery, operations, and CO_2 disposal. Likewise, a similar assessment is recommended of direct carbon removal from the ocean (DOC).
   a. These assessments should include a full life cycle analysis of any products produced from the captured CO_2 and an alternative analysis that addresses other pathways for achieving equivalent or greater CO_2 reductions such as mangrove restoration.

2. Weigh the costs and benefits to all sectors, especially local communities and natural resources, before investing in expanding the use of these technologies.
    a. This analysis by regulators, policymakers, and investors must include the costs of achieving true emissions reduction, direct carbon capture, and the value of these actions for ecosystems and livelihoods.
3. Monitor local ecosystems impact, leakage risks and liability, and other risks. Weave precautions into the policy framework that governs the use of these technologies.
4. Fill in what we don't know about the consequences of these operations.
    a. For example, one considerable knowledge gap is the effect of these machines' operations on biodiversity locally for the individual projects in place and more broadly when considering them at scale.
5. Use the precautionary approach in deploying pilot projects to ensure that the experiments do not cause harm to communities, including more climate vulnerable communities.
    a. Design any projects or deployment with the full engagement of indigenous and other communities to ensure that the technology does not harm the vulnerable to avoid changes in activities by the powerful.

B. Key Insights about Direct Air Capture

DAC might conceivably contribute to the removal of the excess and harmful CO_2 in the atmosphere over a long period of time. Therefore, could mitigate the climate and related effects of high CO_2, concurrent with nations pursuing reductions in GHG emissions. However, there are many immediate questions and concerns to be addressed regarding DAC. The 2018 IPCC Special Report included carbon capture and storage as an element of reducing CO_2 in the atmosphere. That report catalyzed the DAC industry and proponents who see it as a viable strategy for meeting the challenges of climate change. Currently the technology is gaining attention in the news and among corporate leaders, such as Bill Gates, who has invested heavily in DAC plants. Furthermore, the US tax code adds an incentive for corporations to be engaged in furthering the use of DAC. On balance, the current DAC technology seems to represent more risks than solutions at this point.

1. The current market for the captured CO_2 is limited and includes uses that result in an addition to emissions, rather than a net reduction.
    a. The energy costs per ton of carbon removed are very high, even when renewables are used.
    b. An increase in tax credits is critical to commercial-scale application because currently it would be too costly.
2. Loopholes and knowledge gaps in regulations and monitoring of environmental harm from the storing and usage of the captured carbon require improvement via research and guidelines prior to implementation at scale.
    a. Preventing or managing potential leakage of stored CO_2, whether into the air or into the ocean, is highly problematic and may never be possible.
    b. Storage and trapping mechanisms of CO_2 underground and in the ocean requires extensive monitoring, analysis, and legal reform to ensure safety of waterways and ecosystem health.
    c. Using the captured carbon to make fuel, to increase fossil fuel extraction, to produce plastic or carbonated beverages results in regenerating excess CO_2 into the atmosphere.

   d. Using the captured carbon in agricultural production in greenhouses could be expanded to help food security in non-arable land.
3. DAC energy costs and environmental harm are currently a significant negative, especially when the plant is powered by fossil fuels.
   a. Renewable energy is highlighted in the future plans of DAC technology, and should be pursued and investigated further.
4. Governing regulations should be detailed to ensure an ethical progression with DAC.
5. In order for DAC to be utilized in developing countries, DAC would have to be subsidized by developed nations because of its high cost.
   a. Climate finance for developing countries might be more effective and equitable when directed to reducing future emissions, protecting and restoring natural carbon sinks and supporting climate adaptation efforts for vulnerable communities.

DAC is an innovative and science-based tool for vital carbon removal to mitigate climate change—a single tool to be deployed with considerable caution. The high cost and necessity of tax credits and investments raises an important consideration to put these public resources towards other solutions for climate mitigation. DAC should be used in cooccurrence with reducing emissions technology such as renewable energy and electric vehicles.

An extensive comparison to other air negative emission technology (NET) is recommended in order to have a fair estimate of economic benefits, environmental harm, energy costs, and carbon removal productivity. As scaling up is currently happening without any of this information, DAC requires immediate scientific research, regulation, and technological advances prior to being fully embraced from a policy and business perspective.

C. Key Insights of Direct Carbon Capture from the Ocean

1. Technology and implementation of direct capture of carbon from the ocean could be informed by the problems of DAC.
   a. Considerable research and pilot scale testing is recommended before policy reform and large-scale production.
2. Bipolar membrane electrodialysis (BPMED) requires local approval of coastal communities as well as international policy reform to be utilized in a safe and sustainable manner.
3. Reducing costs is essential to successfully reduce and remove CO_2, through tax reform, efficient advancement in technology, global implementation, and public and private investment.
4. Direct ocean capture (DOC) requires a comparative analysis to other ocean CDR technology in order to address economic and environmental consequences, especially targeted to the ocean and coastlines.
   a. Addressing the consequences of accidental chemical discharge and the options for direct usage of the captured carbon is essential prior to large scale operation.
5. Utilizing offshore wind power and wave power is recommended to achieve the most negative emissions for carbon removal.

As noted, the ocean is incredibly powerful in Earth's function and in storage of CO_2. The increasing acidity of the ocean is already a vast problem associated with greenhouse gas emissions, and threatens the very basis of the food chain as well as the capacity of the ocean to produce oxygen. Therefore, carefully working to mitigate this technology's effect on the pH of the ocean is vital. Capturing the excess carbon dioxide within the ocean in an efficient manner deserves attention in the news, policy reform, and scientific publications. The many unknowns of deploying this new technology make investments at scale very risky. With the precautionary principle of "first, do no harm" in mind, one must consider seriously the current risks for biological harm or harm to society that come from these direct carbon removal technologies. The unknown viability of these technical solutions, when we have less expensive natural systems such as seagrass or mangrove restoration available for the ocean, may justifiably bring more environmentally cautious investors to the nature-based solutions at this point in time.

References

1. Guston, G. (2019). *The Paris Climate Problem: A Dangerous Lack of Urgency*. Inside Climate News. https://insideclimatenews.org/news/07112019/paris-climate-agreement-pledges-lack-urgency-ipcc-timeline-warning/
2. Feely, R. A., Sabine, C. L., Lee, K., Berelson, W., Kleypas, J., Fabry, V. J., & Millero, F. J. (2004). Impact of anthropogenic CO2 on the CaCO3 system in the oceans. *Science*, *305*(5682), 362–366. https://doi.org/10.1126/science.1097329
3. Fasihi, M., Efimova, O., & Breyer, C. (2019). Techno-economic assessment of CO2 direct air capture plants. *Journal of Cleaner Production*, *224*, 957–980. https://doi.org/https://doi.org/10.1016/j.jclepro.2019.03.086
4. Budinis, S. (2020). *Direct Air Capture – Analysis*. IEA. https://www.iea.org/reports/direct-air-capture
5. Sigurdardottir, R., & Rathi, A. (2021). *The Icelandic Startup Transforming Carbon Dioxide Into Stone*. Bloomberg. https://www.bloombergquint.com/technology/bill-gates-investment-in-carbon-removal-tech
6. Cho, R. (2018). *Can Removing Carbon From the Atmosphere Save Us From Climate Catastrophe?* Earth Institute at Columbia University. https://blogs.ei.columbia.edu/2018/11/27/carbon-dioxide-removal-climate-change/
7. McQueen, N., Psarras, P., Ne, H., Pilorgé, P., Liguori, S., He, J., Yuan, M., Woodall, C. M., Kian, K., Pierpoint, L., Jurewicz, J., Lucas, J. M., Jacobson, R., Deich, N., & Wilcox, J. (2020). Cost Analysis of Direct Air Capture and Sequestration Coupled to Low-Carbon Thermal Energy in the United States. *Environmental Science & Technology*. https://doi.org/10.1021/acs.est.0c00476
8. *Mission 2013 - Air Capture*. (2013). Massachusetts Institute of Technology. https://igutek.scripts.mit.edu/terrascope/index.php?page=Aircapture
9. Qanbari, F., Pooladi-Darvish, M., Hamed Tabatabaie, S., & Gerami, S. (2011). Storage of CO2 as hydrate beneath the ocean floor. *Energy Procedia*, *4*, 0–000. https://doi.org/10.1016/j.egypro.2011.02.340
10. *CO2 trapping mechanisms - CO2 capture project*. (2015). CCP. https://www.co2captureproject.org/co2_trapping.html
11. Realmonte, G., Drouet, L., Gambhir, A., Glynn, J., Hawkes, A., Köberle, A. C., & Tavoni, M. (2019). An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nature Communications*, *10*(1), 1–12. https://doi.org/10.1038/s41467-019-10842-5
12. Johnson, J. (2019). Capturing carbon: Can it save us? *C&EN Global Enterprise*, *97*(8), 38–43. https://doi.org/10.1021/cen-09708-cover
13. Keith, D. W., Holmes, G., St. Angelo, D., & Heidel, K. (2018). A Process for Capturing CO2 from the Atmosphere. *Joule*, *2*(8), 1573–1594. https://doi.org/10.1016/j.joule.2018.05.006
14. S, D., & A, B. (2021). How (Carbon) Negative Is Direct Air Capture? Life Cycle Assessment of an Industrial Temperature-Vacuum Swing Adsorption Process. *ChemRxiv*. https://doi.org/10.26434/CHEMRXIV.12833747.V2
15. O'callaghan, J. (2018). *Storing CO2 underground can curb carbon emissions, but is it safe?* The EU Research & Innovation Magazine. https://phys.org/news/2018-11-co2-underground-curb-carbon-emissions.html
16. GreenFacts. (2021). *Could CO2 be stored in the deep ocean?* Facts on Health and the Environment. https://www.greenfacts.org/en/co2-capture-storage/l-3/6-ocean-storage-co2.htm#0p0
17. Adams, E. E., & Caldeira, K. (2008). Ocean storage of CO2. *Elements*, *4*(5), 319–324. https://doi.org/10.2113/gselements.4.5.319
18. Broehm, M., Strefler, J., & Bauer, N. (2015). Techno-Economic Review of Direct Air Capture Systems for Large Scale Mitigation of Atmospheric CO2. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.2665702
19. Riebeek, H. (2008). *The Ocean's Carbon Balance*. NASA. https://earthobservatory.nasa.gov/features/OceanCarbon

20. Scheelk, B. (2021). Integrated Large-Scale Action on Habitat Restoration and Pollution in Title of the Report the CLME + Region : Baseline and Pre-Feasibility Assessment Report on Authors of the Report the Needs and Opportunites for Investment. *United Nations Environment Programme - Carribean Environment Programme*, *00*. https://www.unenvironment.org/cep/
21. Burns, W., & Corbett, C. R. (2020). Antacids for the Sea? Artificial Ocean Alkalinization and Climate Change. *One Earth*, *3*(2), 154–156. https://doi.org/10.1016/j.oneear.2020.07.016
22. E.Northrop, & K.Lebling. (2020). *How the Ocean Can Help Absorb CO2*. World Resources Institute. https://www.wri.org/blog/2020/10/ocean-carbon-dioxide-sequestration
23. Digdaya, I. A., Sullivan, I., Lin, M., Han, L., Cheng, W.-H., Atwater, H. A., & Xiang, C. (2020). A direct coupled electrochemical system for capture and conversion of CO 2 from oceanwater. *Nature Communications*. https://doi.org/10.1038/s41467-020-18232-y
24. Willauer, H. D., Hardy, D. R., & Williams, F. W. (2017). *Extraction of Carbon Dioxide from Seawater by an Electrochemical Acidification Cell Part II-Laboratory Scaling Studies*.