captura

Carbon Dioxide Removal Pathway: Ocean Health and MRV

10/19/2023

This document was developed by Captura Corporation (hereafter referred to as Captura) with feedback and review by seven external experts. The purpose of this document is two-fold:

1. **It provides a description of Captura's practices for ensuring our ocean operations are safe for the marine ecosystem.** We have included environmental monitoring plans to evaluate the impact of our technology using the best available information and have identified potential co-benefits and risks of our technology, with mitigation pathways and plans.
2. **This document also describes a monitoring, reporting, and verification (MRV) protocol for Captura's Direct Ocean Capture (DOC) technology for marine carbon dioxide removal (mCDR).** MRV specifications will be targeted for commercial scale operations, however, we will also include pilot testing results herein as we ramp up to commercial scale.

It is our intent to provide transparency and accountability with this document, and we invite feedback and reviews on an ongoing basis to MRV@capturacorp.com.

This is a living document that will be revisited and updated when new information is available and at least every six months. We assume a basic level of understanding of marine chemistry in the document and provide resources for review in the appendix.

Table of Contents

1. Summary

To limit global warming to 1.5-2°C by 2100 and avoid the most severe impacts of climate change, it is critical to remove carbon dioxide (CO_2) from the atmosphere in addition to drastically reducing emissions (IPCC 2022). Captura has developed an innovative electrochemical technology, called Direct Ocean Capture (DOC), to conduct marine carbon dioxide removal (mCDR) at large scale.

Captura's approach has the potential to remove significant quantities of CO_2 from the atmosphere with high energy efficiency and low capital cost. Captura's DOC method requires only seawater and renewable energy as inputs. It uses an electrochemical pH-swing based process to remove a measurable stream of CO_2 directly from the upper surface ocean that will subsequently be either sequestered or utilized (Fig.1). While there are several use cases for CO_2 (fuel production, concrete manufacturing, etc.), this document will focus on the CO_2 sequestration path. CO_2-depleted, or decarbonized, seawater is returned to the ocean with the regenerated capacity to absorb CO_2 from the atmosphere at an amount equivalent to the quantity removed through Captura's process (Fig.1). The process does not add chemicals or foreign materials to the ocean and does not create any byproducts. The long-term goal of the company is to remove CO_2 at gigaton scale by leveraging the ocean's natural ability to absorb and store atmospheric CO_2.

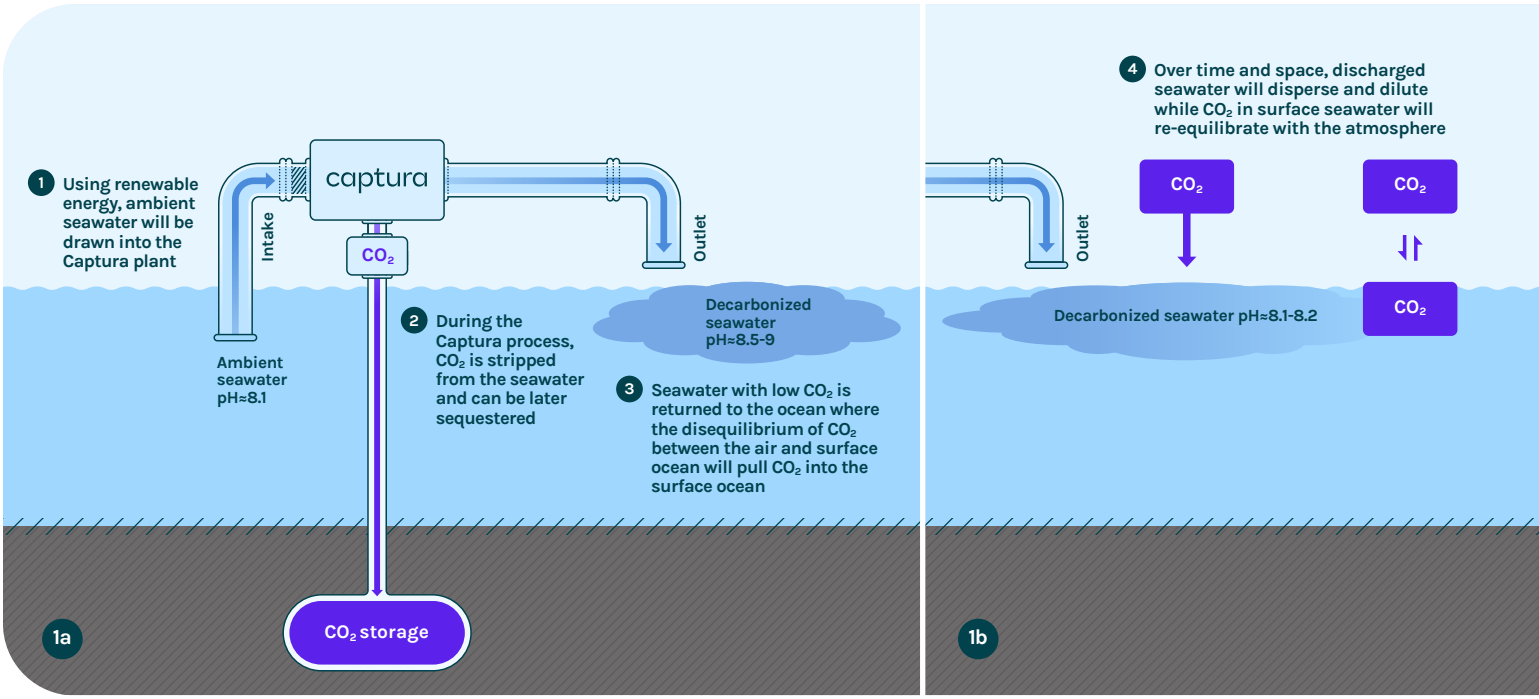


Figure 1. Description of the primary inputs and outputs of Captura's process at points 1-4.

a) A local (tens of meters from the discharge port), near-term (minutes to hours) snapshot

b) Over a larger spatiotemporal scale (kilometers from the discharge port and months to years after initial discharge), decarbonized seawater has spread and diluted, while absorbing CO_2 from the atmosphere during re-equilibration.

Deployments of Captura's DOC technology will include a suite of *in situ* measurements to ensure ocean safety and to inform ocean models to conduct monitoring, reporting, and verification (MRV). Captura is currently conducting a technology piloting program and information gathered from pilots will inform commercial scale operations. For commercial deployments, the Captura MRV team will work closely with independent, third-party organizations and/or government agencies to establish near-field observational modeling and a robust model-based framework to evaluate location-dependent DOC carbon credits. We are collaborating with experts, such as Southern California Coastal Water Research Project (SCCWRP) and others, who are developing MRV models needed to estimate CO_2 removal and additional modeling tasks described in this document. Removal will be verified by an independent third party and data will be compiled into reports that will be made publicly accessible through openly accessible platforms.

2. Process overview

Briefly, during Captura's DOC process (Fig. 2), <1% of seawater intake is diverted for purposes of acid and base feedstock generation, beginning with pre-treatment to soften the seawater by removing dissolved calcium and magnesium salts before electrodialysis. After electrodialysis, seawater has been dissociated into hydrochloric acid (HCl) and sodium hydroxide (NaOH) base through an electrochemical pH-swing process. Then, the following occurs:

1. HCl acid from electrodialysis is added to primary stream of filtered seawater to drive dissolved inorganic carbon (DIC) species into CO_2.
2. CO_2 is extracted at a target of >90% extraction efficiency; the CO_2 stream is captured and will be sequestered geologically (sequestration not shown). Note that during the CO_2 extraction process, dissolved oxygen is also removed.
3. Calcium and magnesium alkaline solids from pre-treatment as well as NaOH base from electrodialysis are added back to the acidified, CO_2-depleted seawater.
4. Alkaline, decarbonized seawater is diluted with ambient seawater to ensure the seawater achieves a target 8.5<pH<9 (range designated for California/US, will be location dependent) and returned to the ocean (the amount of dilution depends on the CO_2 extraction efficiency, where higher extraction efficiency would result in a higher pH and require more dilution). Additionally, dissolved oxygen levels will be increased to appropriate limits for California waters, >5 mg L^{-1}.
5. CO_2-depleted seawater with restored alkalinity and pH levels elevated above local surface ocean pH can then absorb additional CO_2 from the atmosphere relative to the baseline condition without DOC intervention.

2a

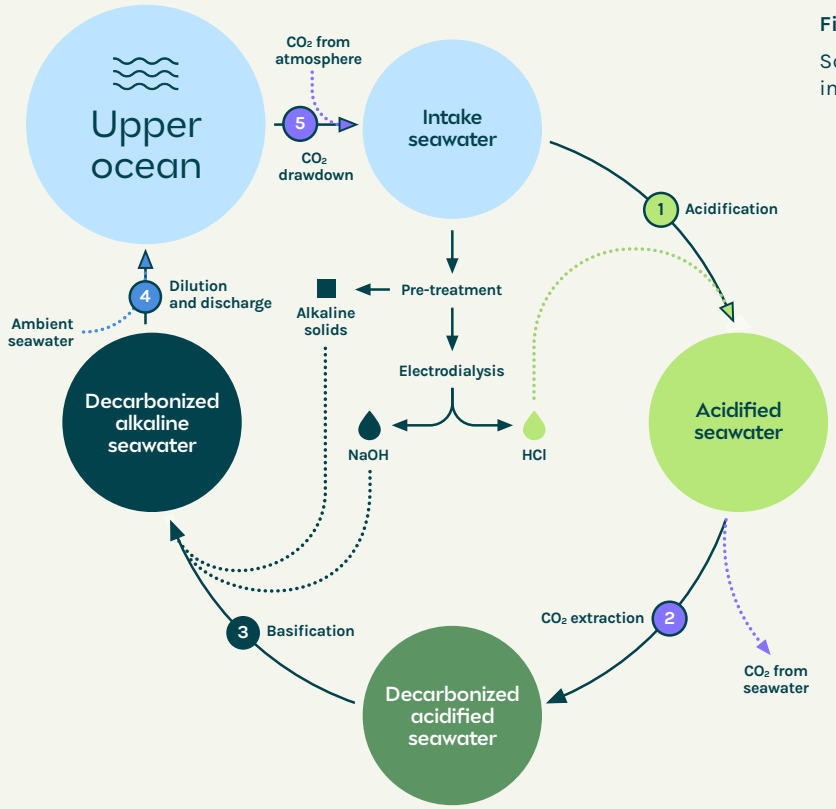


Figure 2a

Schematic of the major steps in the Captura DOC process.

2b

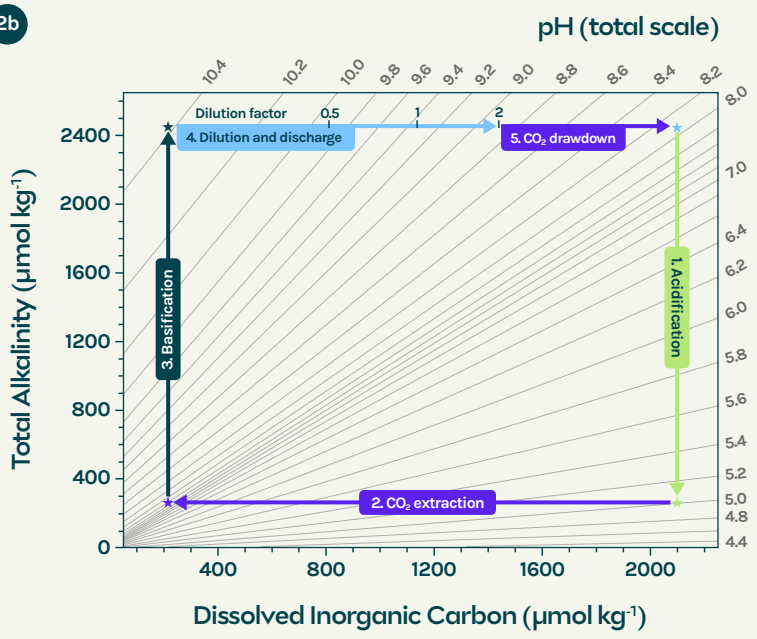


Figure 2b

Composition diagram of the process described in part a) describing the carbonate chemistry calculated for a theoretical 90% CO_2 extraction efficiency with 2X dilution using ambient seawater before discharge and temperature of 25°C, salinity of 35, and 1 atm of pressure. Grey contour lines denote the pH (total scale).

3. Environmental monitoring plans for ocean health

Captura is committed to preserving ocean health and safety. Environmental variables will be measured at the seawater intake and outlet as well as after the discharge to monitor the ecosystem impacts of our technology. Local monitoring will confirm that our processes stay within acceptable limits for permits of existing processes that discharge water into the ocean such as wastewater treatment and desalination plants.

Note: The following describes the current plan for monitoring at the 100-ton/year pilot site in San Pedro, CA. We will adjust it accordingly if other variables are found to be more useful or extraneous. Data collected from monitoring at pilot sites will be published online within six months of collection and incorporated into models for MRV. Lessons learned from this pilot deployment will be used to inform future monitoring plans for other pilots and commercial plants.

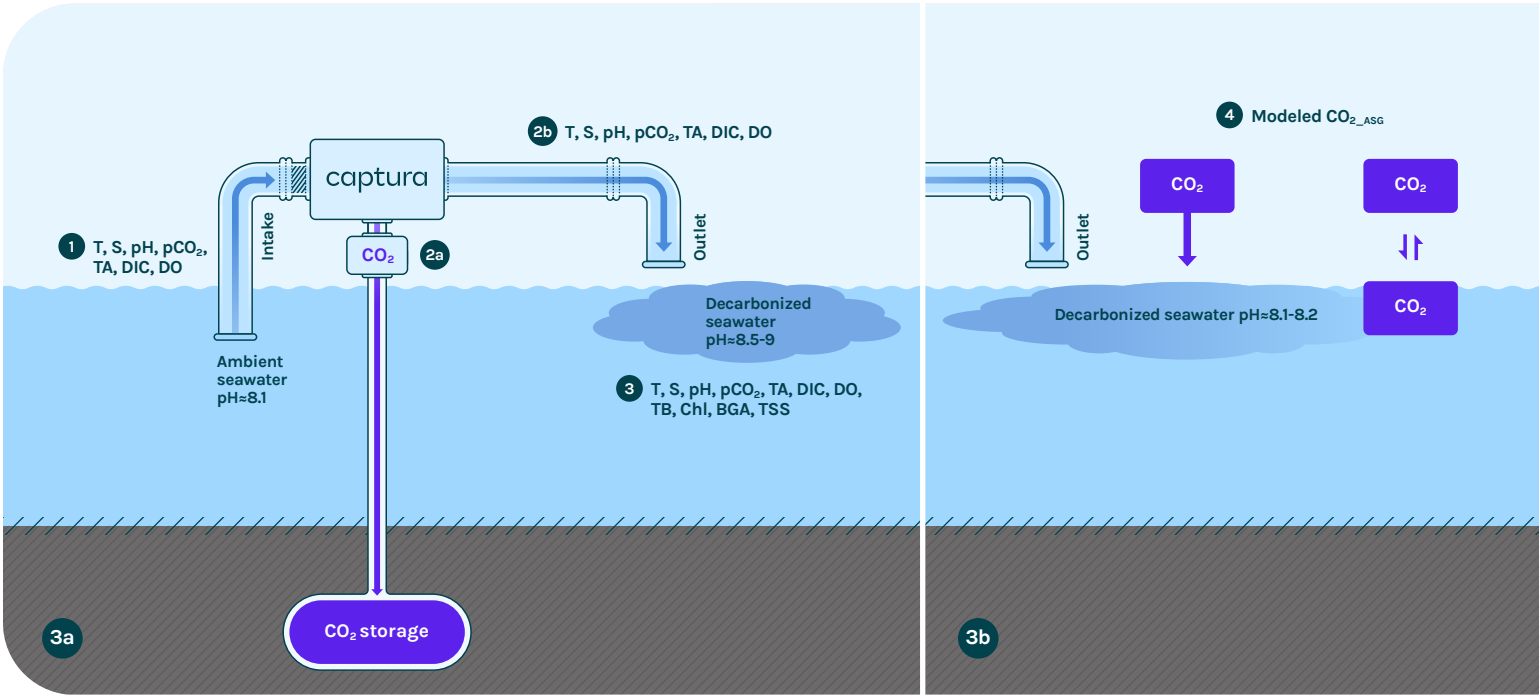


Figure 3. Measurements will be made at different locations of Captura's process in pilot and commercial scales.

a) Measurement point 1 is after the seawater intake and before Captura's DOC process. Measurement points 2a and 2b are after Captura's DOC process that follow the stream of CO_2 gas that is extracted and geologically stored as well as the CO_2-depleted seawater. Point 3 is after the discharge is released back into the ocean (depending on the environment, these measurements may be made in multiple locations with one close to the source and others downstream of the release).

b) Point 4 is model-estimated CO_2 absorbed through air-sea gas exchange (CO_{2_ASG}) into the upper surface ocean from the atmosphere over large scales of time and space.

Table 1. Primary variables to be measured during Captura's process. See locations of measurements in Fig. 3. Target ranges are based on local regulations for wastewater where applicable or based on minimal impacts from the process.

VARIABLE	LOCATION OF MEASUREMENT	MEASUREMENT TYPE	TARGET RANGES FOR DISCHARGE AT POINT 3 (OR 2b, AS INDICATED)
Temperature (T, °C)	1, 2b, 3	Discrete, continuous	± 3°C of local temperature
Salinity (S, PSS-78)	1, 2b, 3	Discrete, continuous	± 5% of local salinity
pH (total scale)	1, 2b, 3	Discrete, continuous	8.5-9
pCO_2 (µatm)	1, 2b, 3	Discrete, continuous	< 10% of local pCO_2 at 2b
Total alkalinity (TA, µmol kg^{-1})	1, 2b, 3	Discrete	± 5% of local alkalinity
Total dissolved inorganic carbon (DIC, µmol kg^{-1})	1, 2b, 3	Discrete	< 10% of local DIC at 2b
Dissolved oxygen (DO, mg L^{-1})	1, 2b, 3	Discrete, continuous	>5 mg L^{-1}
Turbidity (TB, NTU)	3	Continuous	<75 NTU
Chlorophyll a (Chl, µg L^{-1})	3	Continuous	N/A
Blue green algae (BGA, µg L^{-1})	3	Continuous	N/A
Total suspended solids (TSS, mg L^{-1})	3	Discrete	<10 mg L^{-1}
Mass of CO_2 gas removed (g)	2a	Continuous	N/A
Model-estimated CO_{2_ASG} (g)	4	Modeled	N/A

In situ measurements will be provided by continuous sensors [YSI EXO2 Multiparameter Sonde: T, S, pH, DO, TB, Chl, BGA and Turner C-Sense: pCO_2] or with discrete bottle samples as indicated in Table 1 at locations described in Figure 3. Continuous sensors will record approximately hourly measurements. Sensors will be calibrated, maintained, and validated with bottle samples as recommended by the manufacturer to achieve high performance. Baseline monitoring will occur for a period long enough to capture seasonal variability in addition to using existing publicly available data to estimate baseline conditions, when possible. Mass of CO_2 gas removed will be quantified using mass flow meters or similar analytical instruments. Once that CO_2 is sequestered, it will be monitored by sequestration partners according to their standard practices, which require approval by relevant regulation agencies for the sequestration site. Captura will work with model development teams to develop and incorporate economically feasible observational strategies to constrain key elements that will provide calibration/validation datasets for the oceanographic models to quantify model-estimated CO_2 absorbed through air-sea gas exchange (CO_{2_ASG}). These strategies may contain periodic sampling transects, current measurements, or tracer experiments.

4. Primary and potential secondary benefits and impacts

The primary outcomes of Captura's technology are:

1. Remove CO_2 directly from the upper ocean

CO_2 is captured in a gas stream that is quantitively measured by mass flow meters, gas chromatography and/or similar analytical instruments. Uncertainty of this value is negligible due to the accurate metered measurement of CO_2 that is extracted. CO_2 will be sequestered by partners, such as Northern Lights, who will ensure durability of long-term storage of >1000 years at a minimal leakage rate. Storage will be monitored, and leakage will be quantified. Uncertainty depends on the method of storage or utilization but is expected to be minimal.

2. Remove CO_2 indirectly from the atmosphere

CO_2-depleted seawater returned to the ocean from Captura's process will induce atmospheric CO_2 drawdown, and this quantity will be estimated using location specific models. The uncertainty in this estimate can be determined within the model. As mentioned previously, we are partnering with multiple external parties who are developing robust modeling framework and MRV protocols to address this.

The durability of the CO_2 is essentially permanent as it will be converted to bicarbonate and carbonate ions and can be stored on the order of 10,000 to 100,000 years (Falkowski et al. 2000, Caldeira et al. 2018, NASEM 2022).

In addition to the primary carbon removal benefit of Captura's DOC technology, it also provides the environmental co-benefit of mitigating ocean acidification (OA) locally. By releasing seawater with elevated pH back into the ocean, Captura's process directly counteracts ocean acidification. We expect the impact to be localized to the system location and operation. We will use observations collected from the site combined with local modeling to determine the extent of OA mitigation.

Possible localized risks and our plan to address them:

1. Abiotic or biologically mediated calcification—Through our ongoing lab scale tank experiments, we will use literature values (Moras et al. 2022, Hartmann et al. 2023) to test conditions for which secondary precipitation occurs and avoid approaching those limits in pilot field trials and beyond.
2. Filtering, pH swing, and elevated pH/low DIC effects on marine biota—During the CO_2 extraction process, large volumes of seawater are filtered, acidified, and basified. We expect that the effects of our filtering process will be similar to those found in desalination plants. Periodic backwash of the filtering process returns marine biota with characteristic length scale >100 µm back to the ocean. In Captura's process, the residence time of marine biota in acidified seawater is ~10 seconds before base addition. Although there has been extensive research conducted on largely negative impacts of decreased pH or ocean acidification on marine organisms at exposure times of ~days or longer (Fabry et al. 2008, Kleypas et al. 2005, Kroeker et al. 2010 and 2013, Kurihara 2008), there is less information regarding the effects of lower pH on the order of seconds and the effects of high pH and low DIC. With a preliminary model, we have found that the most elevated levels of pH and lowest DIC will be diluted quickly within tens of meters of the discharge port such that maximum impacts will be localized.

We will conduct studies to address the effects of 1) filtering, 2) brief exposure to pH ~4, 3) longer term exposure to high pH/low DIC. For an initial study to look at the biological impacts of these processes, we are leveraging the expertise of a sustainable aquaculture company called **Holdfast Aquaculture** to run experiments on local phytoplankton (green and brown algae, diatoms), bivalves (including mussels and oysters), sea urchins, and seaweed species to determine impacts of Captura effluent, both with and without filtered material, on growth and health of each marine species at different stages of life. We are also exploring opportunities to conduct ecosystem assessments made through a regional ocean model by applying physiological species-specific thresholds to quantify biological effects of modeled exposure to slightly elevated pH and low DIC.

5. Evolving definition of CDR

As the carbon removal industry continues to develop, the definition of carbon removal is also changing. This document refers to carbon removal from the atmosphere via the ocean, however, some organizations have started to adopt a "one-ecosystem" approach that considers removal from the atmosphere and upper hydrosphere (0-200 m) as equivalent. The Carbon Removal XPRIZE allows either and we note that the US Government's first carbon removal purchase program from the Department of Energy (DOE) released in September 2023, defines carbon dioxide removal approaches as those that *"capture CO_2 that is already in the atmosphere or upper hydrosphere and involves the subsequent secure storage of the captured CO_2 in geological, biobased, and ocean reservoirs"*. Captura's core process removes CO_2 from the upper hydrosphere (i.e. the upper surface ocean) and produces a measurable stream of CO_2 for permanent sequestration. Defining carbon credits to include measurable CO_2 removed from the upper surface ocean would simplify the MRV process for Captura and its customers. Until that latter definition is fully accepted, we will continue to consider CDR as the carbon removed from the atmosphere and have described more of the MRV process in the next few sections.

6. Net CO_2 removal mass balance for MRV

To produce high quality carbon credits, MRV will need to assess additionality, leakage, and durability of the mCDR deployment. Additionality indicates the net CO_2 removal above the natural baseline, in other words, how much additional CO_2 would be removed from the atmosphere using an mCDR technique compared to what would happen without the mCDR intervention. Leakage is described as the amount of CO_2 that would escape the removal process. Durability or permanence refers to the length of time that the CO_2 is stored. We address these aspects with respect to quantifying the amount of CDR in the following mass balance (g CO_2):

$$CO_{2\_CDR} = CO_{2\_ASG} - CO_{2\_emissions} - CO_{2\_leakage},$$

where terms are defined as follows:

CO_{2_CDR} – Net atmospheric carbon dioxide removed

CO_{2_ASG} – Amount of CO_2 absorbed from the atmosphere into the upper surface ocean through Air-Sea Gas exchange (ASG, a positive quantity refers to flux into the ocean) or amount of CO_2 that is prevented from outgassing from the ocean. This amount will be based on how much CO_2 is directly removed from seawater in the upper surface ocean (CO_{2_SW}) and the proportion of that quantity that is replenished from the atmosphere, represented by α, such that $CO_{2\_ASG} = \alpha\, CO_{2\_SW}$. We will seek deployment locations with characteristics that would bring α close to 1 (details described in section 10). The completeness of equilibrium of the CO_2-depleted seawater over time and space as well as the quantity of CO_2 drawdown will be estimated through

high-resolution, biogeochemical modeling. Modeling will be used to estimate CO_{2_ASG} for MRV due to the following reasons, among others: 1) the plume of CO_2-depleted seawater will cover a spatial footprint too large to capture with direct observations using currently available sensor technology, 2) to quantify additionality, CDR will need to be evaluated against a baseline scenario without intervention. Several efforts by external parties are currently underway to develop an MRV framework that will enable us to estimate this quantity and the uncertainties associated with it. We describe one such collaboration in section 8 of this document. Durability of the CO_2 absorbed from the atmosphere is considered permanent (>10,000 years, see further details in section 4).

$CO_{2\_emissions}$ – Emissions associated with the energy, materials, and equipment used for Captura's DOC construction, operation, separation, and transport of CO_2 from capture to sequestration site, as well as monitoring and sequestration. A third-party life cycle analysis (LCA) with detailed emissions accounting has been conducted by an environmental engineering consultant and is referenced in the appendix of this document.

$CO_{2\_leakage}$ – Any leakage from CO_2 removed from seawater that is stored geologically. Geologic sequestration is an already established, mature industry with processes that have been developed for 50 years and technology readiness levels (TRLs) of the highest level of 9 (Bui et al. 2018, Keleman et al. 2019, Kearns et al. 2021). Captura will partner with experienced sequestration companies, such as **Northern Lights** project, both onshore and below the seabed to ensure the verifiable and permanent storage of CO_2. Sequestered CO_2 will be in a supercritical liquid state once injected into either depleted oil and gas formations, or into geologic saline aquifers. Sequestration sites will be selected for characteristics that prevent CO_2 from escaping and include monitoring for verification that will be under the responsibility of the sequestration company. Leakage could also include biotic feedbacks, such as alteration of the biological pump, that are presently poorly understood.

In addressing the uncertainties of these terms, we expect that the largest source of uncertainty will be in CO_{2_ASG} term. We note that many forms of carbon removal are not definitive in their quantification of carbon removed and the associated timescale. For example, afforestation requires time for trees to grow and may release CO_2 in the future, Direct Air Capture (DAC) may result in outgassing of CO_2 from the ocean which offsets some of the benefit of atmospheric CO_2 removal. Captura expects that the carbon removal market will reach a consensus on how these uncertainties are addressed in claiming carbon credits (which may include a buffering mechanism for example) and will work with customers and regulatory authorities throughout that process. As models are refined and impacts are better understood, uncertainties will decrease, and the carbon credits will be adjusted accordingly.

7. Emissions assessment

An emissions assessment will be conducted for each commercial Captura plant such that the LCA will be site-specific to include emissions associated with Captura technology and a renewable energy source in addition to the sequestration or utilization component. Major sources of emissions are listed below:

1. Materials and equipment for construction and operation of Captura plant
2. Electricity for Captura's DOC process
3. If sequestering CO_2 geologically, equipment and electricity for compression, pumping, transportation, and injection of CO_2, and CO_2 leakage from pipeline and injection system

Please see Appendix for an example LCA of Captura systems from a third-party report.

8. Reporting and verification

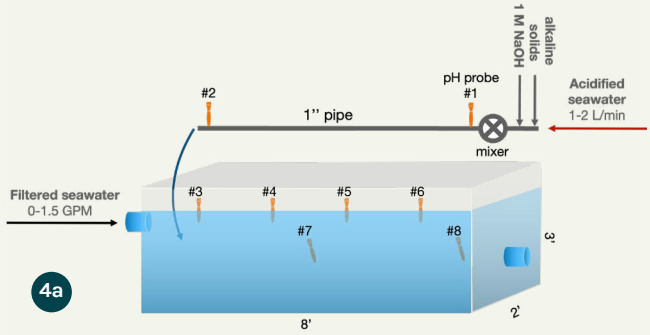
Verification will be performed by a certified validation and verification body (VVB) accredited by a standard body such as the International Organization for Standardization (ISO) 14065. This will confirm that the amount of CO_2 removal that we report is evaluated correctly. Measurements from Table 1 will be reviewed. Verification of the estimated atmospheric CO_2 drawdown will likely include additional model simulations and validation by external parties. Monitoring and verification of the fate of CO_2 that is removed from seawater will differ based on the method of CO_2 storage or utilization.

9. Current state of technology

Results from Captura's laboratory, pilot systems, and modeling work are detailed below and will be updated as new data becomes available.

i. **Preliminary small scale (300 gallon) tank test results from Kerckhoff Marine Laboratory, Newport Beach, CA**

Before discharge to the ocean, different components generated in the Captura process, including 1) acidified CO_2-depleted seawater, 2) alkaline solids (magnesium hydroxide ($Mg(OH)_2$) and calcium carbonate ($CaCO_3$)) from the pre-treatment, and 3) sodium hydroxide (NaOH) solution from electrodialysis, must be mixed together and stay within pre-determined limits from Table 1 to ensure ocean safety.



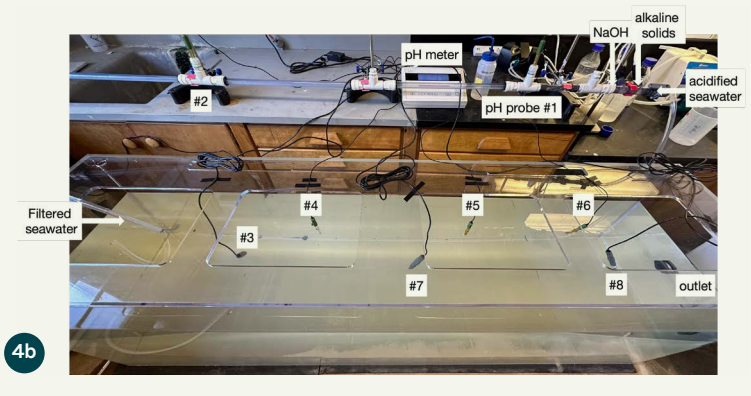
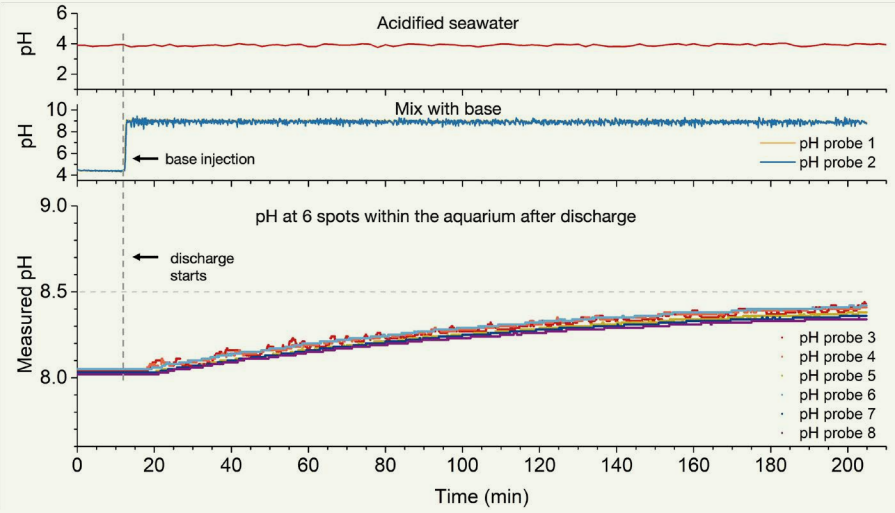


Figure 4

a) Schematic and

b) Picture of lab-scale tank set-up for mixing acidified CO_2-depleted seawater with generated base. Numbered labels refer to positions of pH probes. The acidified CO_2-depleted seawater flows into a 1-inch pipe from the right inlet and mixes with alkaline solids and NaOH base



4c

Figure 4

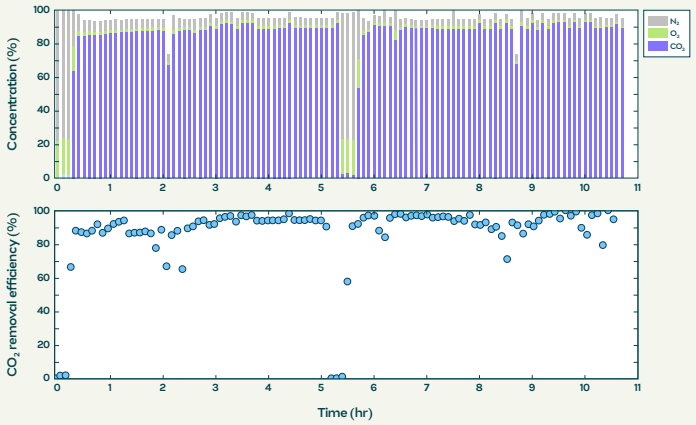
c) Top panel shows the pH of the acidified seawater, second panel shows the pH of the acidified seawater after mixing with alkaline solids and NaOH base measured by pH probe 1 and 2 placed within the 1-inch pipe to monitor the pH after the mixer and before the discharge. The third panel shows measured pH values in the tank over time from pH probes 3-8 as labeled in Fig. 4a and 4b. pH probes 3-6 were placed near the surface of the water in the tank, and pH probes 7 and 8 were immersed under the water.

During this tank experiment (Fig. 4a-b), acidified, CO_2-depleted seawater from the 1-ton pilot (to be discussed further in the next section) operating at 75-80% CO_2 extraction efficiency was directed to the tank. The pH of the acidified seawater was ~4 and increased to ~9 after mixing in the alkaline solids and NaOH (Fig. 4c). The turbidity of the combined effluent was <3 mg/L based on earlier test results. When the effluent mixture was discharged into the tank, pH increased from 8.1 to 8.35-8.4 after 200 min or more than 3 hours. At the current CO_2 extraction efficiency, the discharge pH does not require further dilution. At higher CO_2 extraction efficiency (target for pilot field trials is >90%), pH of the effluent will be higher and may require dilution with ambient seawater to decrease pH to a safe level before discharge. Our next steps for test tank experiments involve monitoring more parameters in addition to pH, including pCO_2, dissolved oxygen, and more accurate flow rates.

ii. Pilot field deployments in Newport Beach, CA and San Pedro, CA

Captura has two existing pilot systems – a 1-ton/year system that has been operating at Caltech's Kerckhoff Marine Laboratory in Newport Beach, CA, and a 100-ton/year system, currently located at AltaSea at the Port of Los Angeles in San Pedro, CA.

The components of a fully scaled system feature high current density electrodialysis technology combined with conventional water/gas handling equipment. The water and gas handling equipment (filters, pumps, CO_2 stripping, vacuum pumps) are all commercially available at Technology Readiness Level (TRL) 9. The overall Captura system is currently moving into TRL 6, having accomplished 2000+ hours of on-site seawater testing with our 1-ton/year CO_2 removal pilot system (Fig. 5a). Initial results from the 1-ton system (Fig. 5b) captured CO_2 concentration from seawater of >90%, from measurements of outflow (the remainder is nitrogen and oxygen which is easily removed), and an overall CO_2 capture rate of >90% as the seawater flows through.



5b

Figure 5

a) Captura's 1-ton/year pilot operating at Newport Beach, California

b) Preliminary results from the 1-ton pilot system show the concentrations of nitrogen, oxygen, and CO_2 on the top panel and CO_2 removal efficiency on the bottom panel

c) Captura's 100-ton/year pilot at the Port of Los Angeles.

Captura's 100-ton/year pilot at the Port of Los Angeles (Fig. 5c) will begin operations in Fall 2023 with the monitoring plan shown earlier in section 2. The 1-ton and 100-ton systems currently use commercially available membranes for electrodialysis and seawater degassing, but commercial scale systems will use Captura proprietary membranes (currently TRL 4) to increase system efficiency by 7-10x.

iii. Preliminary modeling work

Captura has partnered with Southern California Coastal Water Research Project (SCCWRP) to conduct modeling simulations of a commercial scale system. SCCWRP uses a Regional Ocean Model System (ROMS) (Shchepetkin and McWilliams 2005) dynamically coupled to Biogeochemical Elemental Cycling (BEC; Moore et al. 2004), a biogeochemistry and lower-ecosystem model that was enhanced specifically for the California Current System (Deutsch et al. 2021). Please see further details describing the model in the appendix. ROMS-BEC is being applied to evaluate the regional-scale fate of DIC-depleted Captura waters and the temporal and spatial evolution of CO_{2_ASG}, defined in section 2. CO_{2_ASG} is assessed as the difference in the air-sea gas exchange of CO_2 between two ROMS-BEC scenarios. The first scenario is a baseline ocean simulation (hindcast simulation, Kessouri et al. 2021) and the second is a scenario that includes DOC. The difference is considered as CO_2 additionality of DOC relative to baseline conditions.

iv. Future pilots

We have **announced** our partnership with Deep Sky to install a 100-ton pilot in eastern Quebec, Canada in Q3 2024. Additionally, we will be deploying a 1000-ton pilot with the location expected to be announced in November 2023. Following our rigorous piloting program, we expect our first commercial facilities to be operational by 2026.

10. Site selection considerations for commercial scale (>20,000 ton-CO_2/ year) plants

Captura plants can be situated either on-shore or off-shore and can be built as dedicated platforms or can make use of existing infrastructure. In the near term, if built onshore, desalination plants and thermal power plants that use seawater for cooling provide ideal initial deployment locations due to the pre-existing infrastructure for water intake and discharge. Near-shore deployment on decommissioned oil/gas platforms provide the advantage of repurposing equipment and access to a pipeline and geologic reservoir to permanently sequester CO_2 captured from our process.

For future standalone systems, we will use coarser resolution global models as a first screening step to determine suitable deployment locations and then high-resolution regional models to optimize site selection for the greatest efficacy of our technology. Appropriate locations would be established using methods similar to those found in He and Tyka 2023 and Bach et al. 2023, that show how a CO_2 deficit generated by ocean alkalinity enhancement (OAE) in the ocean will equilibrate with the atmosphere over time. An example from Bach et al. 2023 provides modeling for a CDR process similar to DOC that creates a CO_2 deficit in surface seawater to absorb CO_2 from the atmosphere (Note that for the large scale used in this paper, a 100,000 ton-CO_2/year Captura plant would need to operate for 110 years). In Fig. 6 on next page, a 0.25 Tmol pulse of seawater CO_2 deficit was simulated in the Amazon estuary near Fortaleza, Brazil that showed 95% equilibration within 3 years and how the deficit spreads in the surface ocean over the first 10 years.

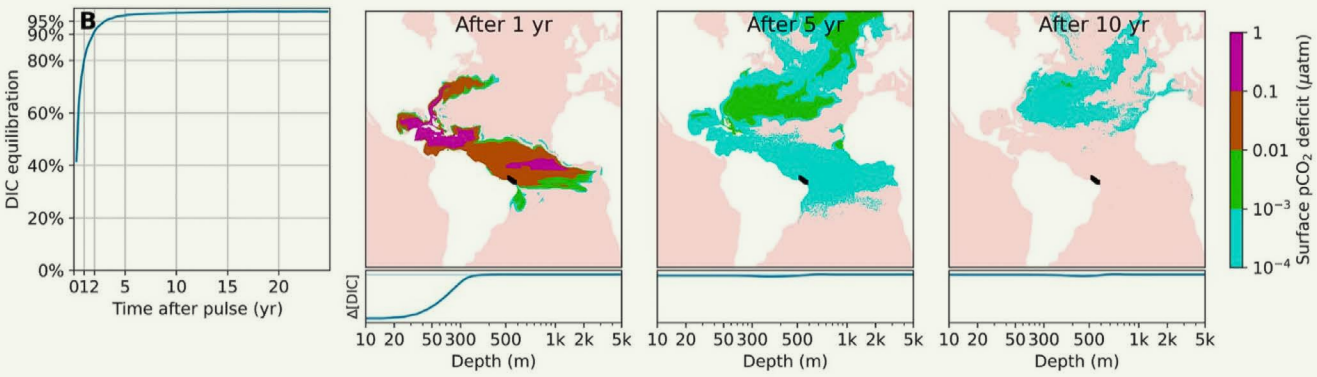


Figure 6 Modified from Bach et al. 2023 Fig. 1b. Simulated equilibration of an initial seawater CO_2 deficit with atmospheric CO_2. (Note that y-axes show DIC instead of CO_2 as DIC was the variable manipulated in the model. However, CO_2 and DIC removal are equivalent when alkalinity remains unchanged.) The initial seawater CO_2 deficit of 0.25 Tmol was simulated in the area marked in black on the maps. The left panel shows the rate of re-equilibration. The maps to the right illustrate the spread of the deficit in the surface ocean indicated by the surface pCO_2 difference relative to the control model run (note the log scale of the color map). The small panels below the maps show the depth of the integrated CO_2 deficit (integrated over the entire ocean). In other words, they show at which depths most of the initial CO_2 deficit occurs.

We will aim for deployment sites with some or all of the following characteristics: 1) no net harm on local ecosystem, to be quantified by comparing baseline field sampling of marine biogeochemistry to operational conditions, 2) operations will not significantly interfere with long-term biogeochemical ocean time-series (i.e. the signal from the plant will not be greater than the observational noise), 3) ocean circulation patterns that will help keep the carbon-depleted water we release at the surface to maintain contact with the atmosphere so that gas exchange can replenish > 90% of process-induced DIC deficit (i.e. negligible downwelling), 4) baseline environment can be established from existing publicly available data or in a timeframe on the order of ~months in order to quantify additionality, 5) co-located with renewable energy sources and efficient access to sequestration/utilization, 6) site can be operational for >10 years with minimal decrease in efficiency.

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12. Appendix

i. Resources for marine carbon cycling

To better understand Captura's process and what its effects will be on the ocean, it is important to first understand the marine carbon cycle. For a refresher on marine carbon cycling, please refer to:

1. **NOAA education resources on carbon cycle**
2. **Part 1 seawater carbonate chemistry from Guide to best practices for ocean acidification research and reporting**

ii. Southern California Coastal Water Research Project (SCCWRP) ROMS BEC model description

A physical-biogeochemical numerical ocean model is being utilized to assess the amount of CO_2 absorbed from the atmosphere into the ocean through air-sea gas exchange. The physical model, the Regional Ocean Model System (ROMS), is a widely used, open-sourced code, for U.S. coastal waters and elsewhere (Shchepetkin and McWilliams 2005). The general ROMS functionality is a computational solution of the incompressible hydrostatic equations with a free upper surface, realistic equation of state, and parameterization for small-scale turbulent mixing, especially in the top and bottom boundary layers. ROMS includes dynamics coupling to surface gravity waves (McWilliams et al. 2004) and extends from the open sea into the littoral zone with wave breaking (Uchiyama et al. 2010). It requires spatially detailed patterns of wind and surface buoyancy forcing, obtained from simulations of the regional Weather Research and Forecast model (WRF; Skamarock and Klemp, 2008). ROMS is dynamically coupled to Biogeochemical Elemental Cycling (BEC; Moore et al. 2004), a biogeochemistry and lower-ecosystem model that was enhanced specifically for the California Current System (Deutsch et al. 2021). It simulates the cycles of organic and inorganic carbon, alkalinity, oxygen, and nutrients (nitrate, ammonium, phosphate, silicate, and iron) as driven be phytoplankton (diatoms, diazotrophs, small phytoplankton, and coccolithophores) and zooplankton functional groups. Deutsch et al. (2021) enhanced BEC by linking the ecosystem to a carbon system module that tracks dissolved in organic carbon and alkalinity, and an air-sea gas exchange module that allows realistic representation of dissolved gases (e.g., O2, CO_2, and nitrous oxide), based on the formulation of Wanninkhof (1992). Model nests scale from a 4-km horizontal resolution spanning the entire CCS, to a 1-km resolution grid covering much of the California coast, to a 0.3-km grid in the Southern California Bight (Kessouri et al. 2021a,b).

ROMS-BEC has been validated at a coast-wide scale for atmospheric forcing, physics, and biogeochemistry, including O2, DIC, primary productivity, and hydrographic parameters (Deutsch et al., 2021; Renault et al., 2021) and within the Southern California Bight, on nearshore, to investigate wastewater outfall plume impacts of coastal eutrophication on ocean acidification and oxygen loss (Kessouri et al. 2021b). At both scales, ROMS-BEC has demonstrated exceptional ability to reproduce the mean distributions and variability of key biogeochemical and ecosystem properties, including core carbonate system parameters germane to this proposed application. The model is run with a time step of 30 s, and outputs are saved as 1-day averages. More information on the model setup and forcing is provided in other works (Deutsch et al. 2021, Renault et al. 2021, Kessouri et al. 2021b). For the 1-km and 0.3-km model nests, 20+ years of hindcast simulations have been conducted (1997-2017), capturing variability on time scales of daily to decadal.

iii. Frontier carbon removal application

Frontier carbon removal purchase application with LCA starting on page 14 (**link**)