SeaO2

Carbon dioxide removal prepurchase application

Summer 2024

General Application

(The General Application applies to everyone; all applicants should complete this)

Public section

The content in this section (answers to questions 1(a) - (d)) will be made public on the Frontier GitHub repository after the conclusion of the 2024 summer purchase cycle. Include as much detail as possible but omit sensitive and proprietary information.

Company or organization name

SeaO2

Company or organization location (we welcome applicants from anywhere in the world)

The Netherlands

Name(s) of primary point(s) of contact for this application

Monica Larrazabal, Rose Sharifian

Brief company or organization description <20 words

SeaO2 is a Direct Ocean Capture company, harnessing the vast potential of the oceans to remove CO2 from the atmosphere at gigaton-scale.

1. Public summary of proposed project[1] to Frontier

a. **Description of the CDR approach:** Describe how the proposed technology removes CO_2 from the atmosphere, including how the carbon is stored for > 1,000 years. Tell us why your system is best-in-class, and how you're differentiated from any other organization working on a similar approach. If your project addresses any of the priority innovation areas identified in the RFP, tell us how. Please include figures and system schematics and be specific, but concise. 1000-1500 words

SeaO2's solution is Direct Ocean Capture, which relies solely on renewable electricity and seawater to extract CO2 from seawater and consequently from the atmosphere in a scalable and cost-effective way.

[1] We use "project" throughout this template, but the term is not intended to denote a single facility. The "project" being proposed to Frontier could include multiple facilities/locations or potentially all the CDR activities of your company.

The ocean is a powerful ally in carbon removal not only due to its vast scale, but also because it has an existing carbon removal power: It already absorbs a third of all anthropogenic emissions in the globe, acting as an air contactor and an absorbent of CO2. Most importantly, this means carbon is 150 times more concentrated than the air, presenting a unique opportunity for removal.

Our technology overview

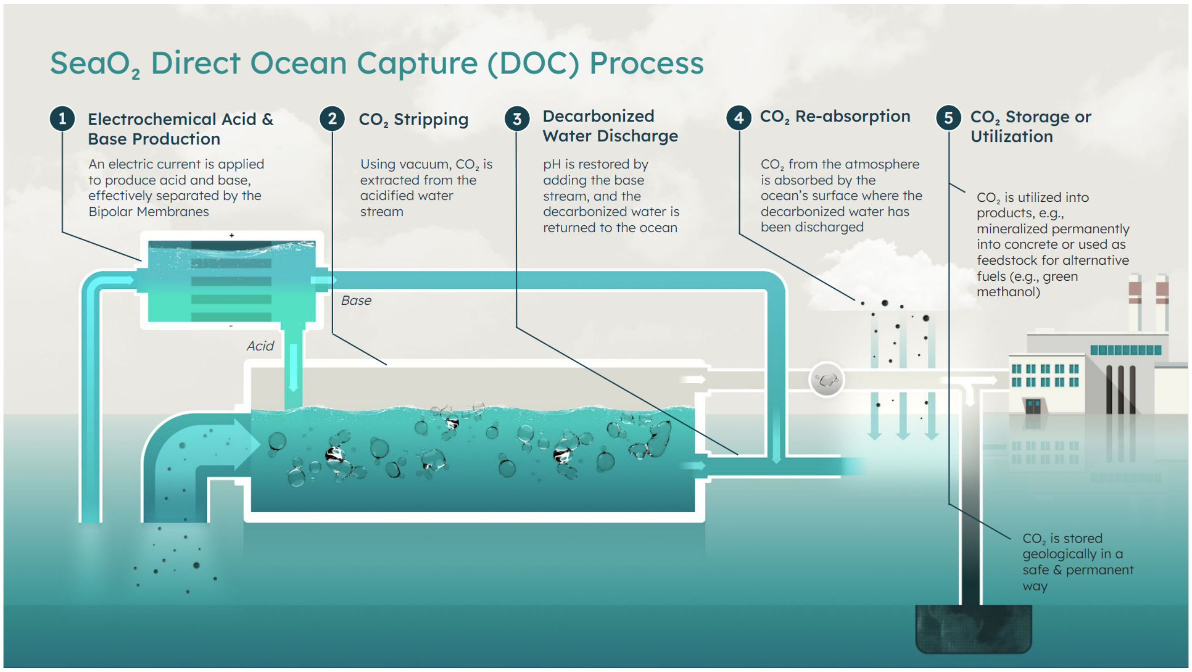

Figure 1: Description of SeaO2's Direct Ocean Capture Process

The process uses electrochemistry to produce an acid and base from a small stream of water (<1% of water processed), by applying electricity to seawater in the electrochemical stack, which is equipped with multiple charged bi-polar membranes that effectively separate the acid and base streams. The acid stream is used to shift the carbonate equilibrium in a larger stream of water, transform the existing Dissolved Inorganic Carbon (DIC) into gaseous CO2 and extract it in gas form with the help of vacuum. After restoring the pH of the decarbonized water with the basic stream previously produced, the water is returned to the ocean, where it re-equilibrates from the atmosphere, effectively reabsorbing an equivalent amount of CO2. The extracted CO_2 is permanently stored in geological formations or utilised into products such as concrete with third party providers.

The Principle to extract CO2: electrochemical pH-swing (Steps 1 & 2 in Figure 1)

Water contains several carbonic species in the equilibrium shown below

- Carbon Dioxide: CO2(g)⇌CO2(aq)
- Carbonic acid: CO2(aq)+H2O⇌H2CO3
- Bicarbonate: CO2(aq)+OH-⇌HCO3 -
- Water: OH-+H+⇌H2O

The total DIC is described as the sum of the concentration of all present carbonic species:

DIC = [H2CO3*]+[HCO3-]+[CO32-], where H2CO3* = H2CO3 + CO2(aq).

Our technology removes the DIC from the ocean in the form of gaseous CO2 via an electrochemical pH-swing. In an open system, the total concentration of the DIC varies by changing in the pH; Acidification results in CO2(g) out-gassing, while basification leads to more CO2(g) absorption, increasing the DIC. In a closed system (e.g., inside of the SeaO2's electrochemical cell), the total DIC remains constant regardless of any pH changes. If so, the dominant carbonic species are altered by changing the pH as demonstrated in Figure 2.

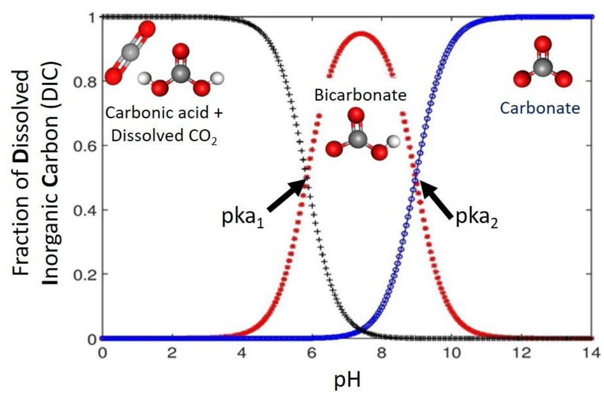

Figure 2 Effect of pH on the CO2 equilibrium (for a closed system at temperature of 25 °C and salinity of 35 ppt i.e., similar to the seawater).

Upon acidification, all bi/carbonate ions in the seawater turn into dissolved CO2 and carbonic acid which then can be vacuum stripped.

From water CO2 stripping to atmospheric Carbon Removal (Steps 3 & 4 in Figure 1)

After CO2 gas stripping, all the produced alkalinity from the electrochemical stack (i.e., OH-) is added to the decarbonised stream again to rebalance its pH and ensure fast paced short-term atmosphere-ocean CO2 re-equilibration.

The returned water stream has a very low DIC, a higher pH, and an (almost) unchanged alkalinity which differentiate our method from ocean alkalinity enhancement (OAE) methods. Because of this minimal alteration that is focused only on carbon content, we expect reduced environmental impacts, since we introduce no chemicals/minerals and change the alkalinity very lightly.

The decarbonized stream can be directed back to the surface ocean where it can re-equilibrate with the atmosphere to absorb CO_2(g). The low concentration of CO_2 in the discharged water absorbs CO_2 from the atmosphere until the amount of CO_2 that was removed is restored to the ocean again, following Henry's Law. This 'replacement' CO2 that comes from the atmosphere turns into bicarbonate, which provides permanent storage for >10,000 years

In Figure 3, we can observe the full carbonate changes that the water goes through in our system.

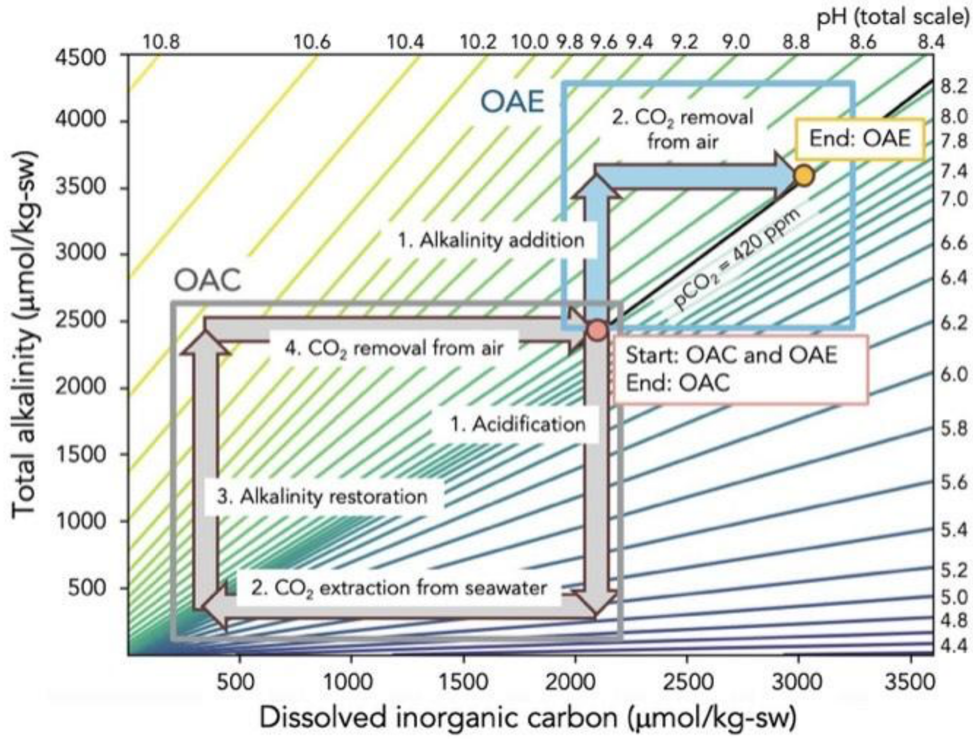

Figure 3: Schematic for TA-DIC-pH pathway for OAC (also known as DOC, Direct Ocean Capture or DOR, Direct Ocean Removal) and OAE. Ref: Eisaman MD (2024) Pathways for marine carbon dioxide removal using electrochemical acid-base generation

The extracted CO2 will be sequestrated with a third party using validated methods with either utilization using an ex-situ mineralization process that chemically binds the CO2 into concrete (e.g., our partner Paebbl) or geological sequestration using in-situ mineralization (e.g., Carbfix). Both storage options mentioned above have >10,000 years permanence for the extracted CO2.

Value proposition & Differentiators

Leveraging the ocean's vast potential, Direct Ocean Capture can be applied cost-effectively and at-scale with minimal environmental impact.

- Compact plug-and-play design allows for retrofitting into existing marine infrastructure and for minimal land use.
- No need for feedstock, absorbents or by-products generation, simplifying operations.
- Fully electrical and heat-free, can operate intermittently, leveraging the cleanest and most cost-effective energy sources while serving for grid-balancing
- Introduces no chemicals/minerals and minimally affects alkalinity, minimizing potential environmental uncertainties and paving the way for pioneering scientifically-endorsed robust MRV
- Generates a pure CO2 stream, enhancing measurability compared to purely modeled CDR solutions, which can help build market trust in marine approaches often scrutinized for quantification. This also provides an alternative revenue stream by supplying green CO2 for utilization purposes, offering a competitive edge and market risk diversification for investors.

SeaO2's approach stands out within the Direct Ocean Capture pathway due to our focus on process optimization and our strategic geographical positioning.

- **Innovative Process Engineering**: We are pioneering advanced process engineering techniques to significantly reduce energy consumption, mitigate fouling within our electrochemical stacks and enable scalability. This not only enhances the efficiency of our operations but also extends the lifespan and reliability of our technology, setting us apart. Further details on these innovations are available in the confidential section.
- **Strategic Location in The Netherlands:** Our base in The Netherlands, a global leader in water management & offshore infrastructure, provides us with unrivaled access to cutting-edge expertise and robust partnerships. This environment fosters continuous innovation and allows us to leverage the country's extensive knowledge and infrastructure in water management. Although The Netherlands does not necessarily need to be the final scaling location in the long term, its strategic advantages make it the ideal location for advancing our DOC technology.

The vision: Scaling by partnering with industry

Our future vision is to co-locate offshore together with other marine infrastructure by retrofitting offshore oil & gas platforms into Direct Ocean Capture Hubs, where we can be co-located with wind-farms for renewable energy (and help for grid balancing) and with geological CO2 storage. As an example, there are already two projects in The Netherlands developing offshore geological storage - Porthos, which has a total capacity of 37 Megatons of CO2 and is already sold out with point-source CO2, and Aramis, which is to be commissioned in 2027 and will have a capacity of 400 Megatons of CO2. We may also consider other key regions for DOC Hubs

At a tactical level in the short to medium term, we will integrate with industries that are already pumping saltwater for their facilities - such as thermal plants using water for cooling, desalination plants, waste water management facilities and aquaculture.

Beyond carbon: co-benefits & environmental impacts

Environmental / economic co-benefits: SeaO2's solution has several non-Carbon Benefits:

- Ecosystem De-acidification: Since our process involves discharging CO2-depleted water with a slightly higher pH, our project can help mitigate ocean acidification, benefiting local marine ecosystems and livelihoods.
- Enhanced Ocean Monitoring: Given our requirements for Monitoring, Reporting and Verification (MRV), our activity can increase ocean observation in areas with limited oversight, fostering better understanding and protection of marine environments.
- Blue Economy & Jobs: SeaO2 offers economic opportunities and job creation in the blue economy estimated in 1,300+ [1] jobs in 2030 across operations, construction and indirect jobs.

[1] Based in extrapolations from Stockholm Exergi jobs projections with our own
https://www.stockholmexergi.se/content/uploads/2022/02/BECCS-Economics-Sweden-final.pdf

b. **Project objectives:** What are you trying to build? Discuss location(s) and scale. What is the current cost breakdown, and what needs to happen for your CDR solution to approach Frontier's cost and scale criteria?[2] What is your approach to quantifying the carbon removed? Please include figures and system schematics and be specific, but concise. 1000-1500 words

Current Project goals & Deployment Strategy

We are currently in design and procurement phase of our Pilot facility which will have a gross carbon removal capacity of 250 tons of CO_2 per year and will start operations end of 2024. This pilot will be located in The Netherlands

At scale, we will deploy in locations that optimize for access to low-cost renewable electricity, access to storage, optimal oceanographic conditions, favorable policy and infrastructure partnership opportunities (e.g., ability to share pumped water capacity, retrofit of existing infrastructure, offshore co-location)

Cost breakdown & Key Cost reductions

In our pilot plant, Capex constitutes ~70% of our cost, driven by logical inefficiencies of deploying at small scale. Opex is mostly comprised by high energy costs (16%) followed by labor cost (7%). At FOAK, costs will have fallen drastically but maintain roughly a similar structure of 70+% capex, 13% energy

The main cost reductions to tackle from current state to achieve TRL9 will be:

- Reduce to Half the Electricity consumption
- Compact design that can be retrofitted in already existing industries and/ or on retired oil and gas offshore platforms
- Achieve industrial integration with with water-pumping industries
- Realize key Capex optimizations
- Reduce membrane Prices to half vs. pilot based on negotiation power
- Reduce stack fouling to increase membrane durability and reduce membrane replacement
- MRV Monitoring Equipment keeps at 1-2 buoys per site, cost of sensors drops

At NOAK, once CAPEX costs have started to go down due to learning dynamics, we estimate to have a total cost of 150$/ton comprised by 50$ Capex and 100$ Opex, out of which ~$60/ton will be in energy followed by costs on membrane and storage. The main aspects that will drive down costs are

- A fast Learning rate for Capex driven by modularity and rapid scale-up
- Locating Offshore to enable scalability, colocating with storage and leveraging low-cost, renewable energy sources
- Membrane engineering to increase its durability and efficiency (bringing the ohmic/ non-ohmic losses down)
- Higher DIC removal yield and CO_2 purity as a result of improved robust degasser designs

More detail of how costs scale in time can be found in confidential section

MRV CO2 quantification approach

We have defined an approach to quantify the CO_2 that is permanently removed from the atmosphere

[2] We're looking for approaches that can reach climate-relevant scale (about 0.5 Gt CDR/year at $100/ton). We will consider approaches that don't quite meet this bar if they perform well against our other criteria, can enable the removal of hundreds of millions of tons, are otherwise compelling enough to be part of the global portfolio of climate solutions.

- #1 Accurate, permanent and leakage-free storage of pure Stream of CO_2. This element is common to DAC approaches given that we also are able to measure directly the outlet of the CO_2 Stripping process. Verification will follow already existing third-party methodologies of Concrete Mineralization or Geological Storage
- #2 Air-Sea CO_2 Re-equilibration calculation to quantify the fraction of CO_2 removed from the ocean that also entails a removal from the atmosphere, with no reversal risk. This element will be derived from a combination of oceanographic modeling with numerical simulations of effluent dispersion and regional oceanographic conditions, and direct monitoring with ocean sensing measurements of Total Alkalinity, pH, DIC and pCO_2.

Notably, we are following a partnership-oriented approach to tackle MRV, more details can be found in section 5.

c. **Risks:** What are the biggest risks and how will you mitigate those? Include technical, project execution, measurement, reporting and verification (MRV), ecosystem, financial, and any other risks. 500-1000 words

Main risks for our pilot deployment are:

- Pilot Permitting: Securing the necessary permits can take longer than expected and postpone our plans. For the pilot, this process is already underway together with our co-location partner and we have engaged an external advisory expert in this field. To mitigate risk of delay due to this dependency, we are working in parallel to explore possibilities of permitting elsewhere
- Pilot Co-location Agreement: The agreement with our prospective co-location partner could be jeopardized if the permitting process encounters issues. We maintain transparent and continuous communication with our co-location partner to keep them informed of our progress. We are also exploring alternative co-location options to ensure we have backup plans in place.
- CO_2 Sequestration partner: Securing sequestration capacity might be at risk due to capacity building. We are in active conversations with Paebbl and Carbfix to establish reliable partnerships, while enabling for flexibility to reduce reliance on a single storage provider.
- Membrane supply constraints. Dependency on a single membrane supplier could lead to supply chain disruptions or pricing issues in the long term. We are actively partnering with our membrane supplier and exploring alternatives to mitigate dependency on a single source and address potential pricing or availability concerns.
- Technical Execution risk: Novel solutions may require more time for design, construction, assembly, and troubleshooting than anticipated, risking project timeline overruns. We are implementing robust project management practices, including detailed planning, regular progress reviews, and risk assessments. By closely monitoring the project timeline and having contingency plans, we can address issues promptly as they arise. We also engage with experienced contractors and consultants to ensure high-quality execution.
- Funding: Securing adequate funding for the pilot remains a critical challenge, particularly in the current European VC environment. Upfront liquidity (e.g., via pre-purchases) is essential for unlocking market potential and attracting further investment to continue building the pilot
- Monitoring, Reporting and Verification & Environmental Impacts: Evidencing volume of captured CO_2 from the atmosphere while ensuring no harmful environmental impacts (or even positive) could be both challenging and costly, as it is not standardized. Additionally, low re-equilibration efficiencies affect our unit economics. Our goal is to tactically ensure we implement best practices for our pilot and maximize learning, while also helping create the ecosystem-level structures to build trust in marine carbon removal approaches, and we are developing the right partnerships to do so.

• Social License: Gaining public and regulatory acceptance for marine CDR projects could pose a significant risk. We are emphasizing a responsible deployment strategy, engaging with local communities, stakeholders, and regulatory bodies early in the process. By setting high standards and demonstrating our commitment to environmental stewardship, we aim to build trust and gain social license for our operations.

d. **Proposed offer to Frontier:** Please list proposed CDR volume, delivery timeline and price below. If you are selected for a Frontier prepurchase, this table will form the basis of contract discussions.

Proposed CDR over the project lifetime (tons) *(should be net volume after taking into account the uncertainty discount proposed in 5c)*	[public answer] 222 tons
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	2025-2027
Levelized cost ($/ton CO_2) *(This is the cost per ton for the project tonnage described above, and should match 6d)*	7,284 $/ton
Levelized price ($/ton CO_2)[3] *(This is the price per ton of your offer to us for the tonnage described above)*	1800 $/ton *Rationale for lower price: (1) we believe such a “distorted” high cost caused by inefficiencies of a pilot might bring bad public reputation and misunderstandings (2) we have already pre-sold some credits at this price for the same facility (3) we aspire to fund the capex for the pilot through grants (cost of capital 0)*

[3] This does not need to exactly match the cost calculated for “This Project” in the TEA spreadsheet (e.g., it’s expected to include a margin and reflect reductions from co-product revenue if applicable).