



SeaO2

Carbon dioxide removal prepurchase application

Summer 2023

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 2023 summer purchase cycle. Include as much detail as possible but omit sensitive 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

Ruben Brands (ruben@seao2.nl) & Rose Sharifian (rose@seao2.nl)

Brief company or organization description <20 words

SeaO2 is a Dutch startup that removes atmospheric CO₂ by leveraging the ocean as an absorbent using an electrochemical method.

1. Public summary of proposed project¹ to Frontier

- Description of the CDR approach:** Describe how the proposed technology removes CO₂ from the atmosphere, including how the carbon is stored for > 1,000 years. Tell us why your system is

¹ We use “project” throughout this template, but note that 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.

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. Aim for 1000-1500 words.

Our technology removes the dissolved inorganic carbon from the ocean in the form of gaseous CO₂ via an electrochemical pH-swing (Figure 1). The amount of removed carbon dioxide is accurately measurable. Consequently, the oceanic carbon removal reduces the atmospheric CO₂ concentration through the equilibrium between the ocean and the atmosphere.

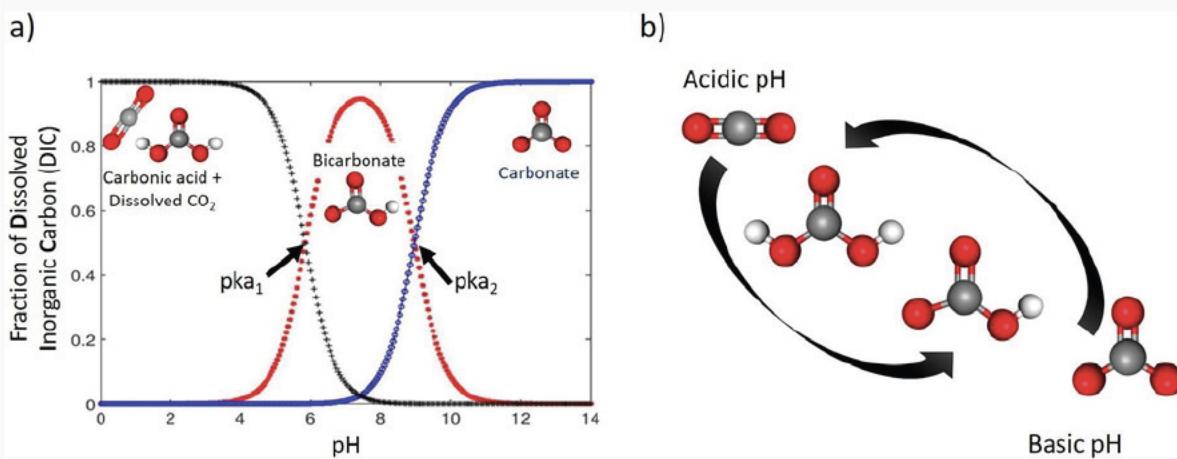


Figure 1 (a) Effect of pH on the CO₂ equilibrium (for a closed system at temperature of 25 °C and salinity of 35 ppt i.e., similar to the seawater). The solution is buffered around two pKa values. (b) Schematic of the pH-swing concept. Upon acidification, all bi/carbonate ions in the sea turn into dissolved CO₂ and carbonic acid which then can be vacuum stripped. DIC is the sum of dissolved CO₂, bicarbonate and carbonate species.

The total dissolved inorganic carbon, DIC, is described as the summation of the concentration of all present carbonic species:

$$\text{DIC} = [\text{H}_2\text{CO}_3^*] + [\text{HCO}_3^-] + [\text{CO}_3^{2-}],$$

Where H₂CO₃^{*} = H₂CO₃ + CO₂(aq). In an open system, the total concentration of the dissolved inorganic carbon 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 alter by changing the pH as demonstrated in Figure 1 (a). The equilibrium can be shown through below reactions:

- $\text{CO}_2(\text{g}) \rightleftharpoons \text{CO}_2(\text{aq})$
- $\text{CO}_2(\text{aq}) + \text{H}_2\text{O} \rightleftharpoons \text{H}_2\text{CO}_3$
- $\text{CO}_2(\text{aq}) + \text{OH}^- \rightleftharpoons \text{HCO}_3^-$
- $\text{OH}^- + \text{H}^+ \rightleftharpoons \text{H}_2\text{O}$

SeaO₂'s extraction process involves using an electrochemical stack containing multiple charged membranes that converts oceanic bi/carbonate into CO₂ (Figure 2 and 3). The gas is then stripped and separated from the water. Once the decarbonized, pH-rebalanced, seawater is returned to the surface mixed layer of the ocean, it will again absorb CO₂ from the atmosphere, enabling an indirect oceanic carbon capture with a 1:1 ratio. The returned water stream has a very low DIC, a higher pH, and an (almost) unchanged alkalinity which differentiate our method from the ocean alkalinity enhancement (OAE) methods. Thanks to the low concentration of CO₂ in the returned water and its higher pH, the treated ocean draws CO₂ from the atmosphere until the amount of CO₂ removed is restored to the ocean again (typically 2-4 months timescale, maximum 1 year depending on the capture plant location).

SeaO₂'s technology does not alter the ocean alkalinity as it is not an OAE method and no calcium or magnesium is removed in the process either. Furthermore, less than 1 % of the total oceanic volumetric flow needs to be filtered and enter the electrochemical stack for acid and base production. The extraction of the CO₂ product stream from the acidified ocean water requires vacuum and downstream dehydration to achieve acceptable purity for transportation and storage. The capture plant can be co-located or stand alone. For our 250 tCO₂/yr pilot, we will design a co-localized facility.

In the electrochemical stack, 1 mole electrons (i.e., applied current) results in 1 mole H⁺ and 1 mole OH⁻ ions (from the water dissociation reaction in the bipolar membrane). Subsequently, the H⁺ ions turn bi/carbonate ions into H₂CO₃+CO₂(aq). After gas stripping, all the produced alkaline (i.e., OH⁻) is added to the decarbonised stream to rebalance its pH and ensure fast paced short-term atmosphere-ocean CO₂ exchange.

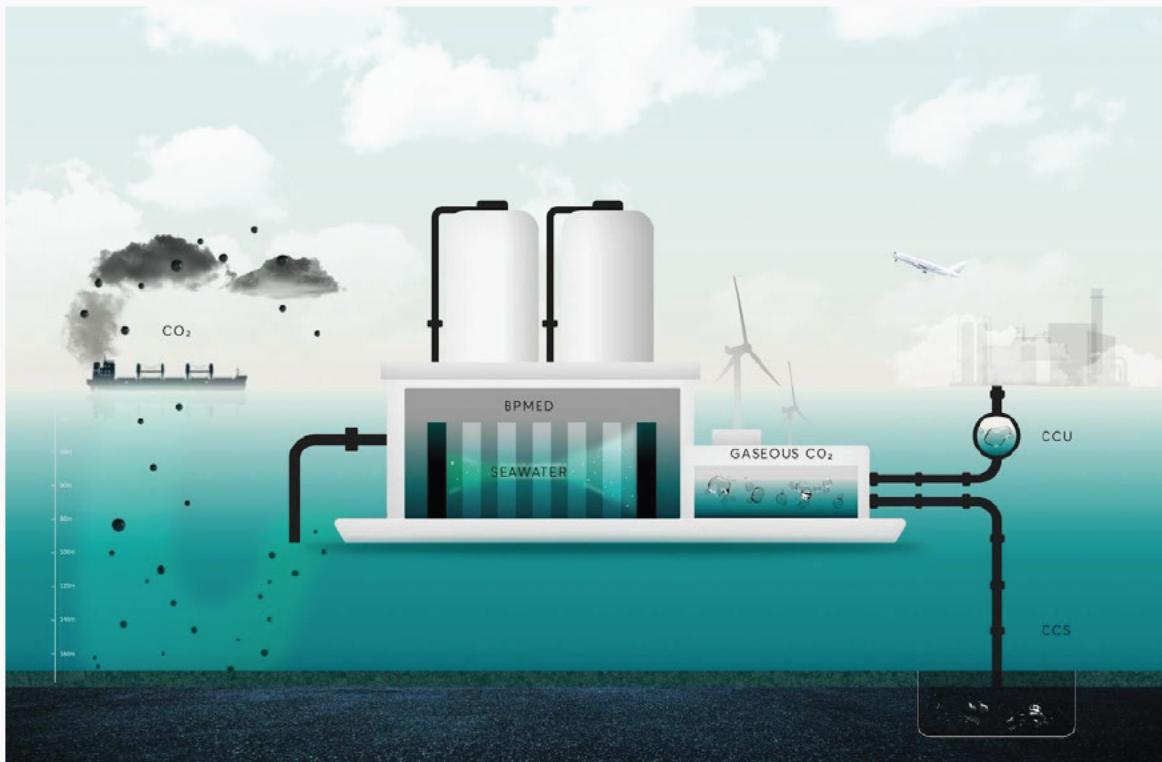


Figure 2 In CO₂ capture from seawater, the ocean already acts as CO₂ absorbent, leveraging its gigantic surface. To extract the CO₂ from the sea as a gas, the bi-/ carbonate ions present in the seawater is converted into H₂CO₃ in the acidic compartments of a bipolar membrane (BPM) stack. Subsequently, CO₂(g) can be stripped out of the acidified stream. The produced base in the BPM-stack is then used to restore the seawater pH again. By removing the CO₂ from the ocean, we bring balance to it and battle ocean acidification. The returned ocean water in our process has a very low carbon content, a slightly higher pH, and unchanged alkalinity. The CO₂ can be stored away: carbon capture and storage (CCS/CDR). Or CO₂ can be used/ converted to chemical/ fuels: carbon capture and utilization (CCU).

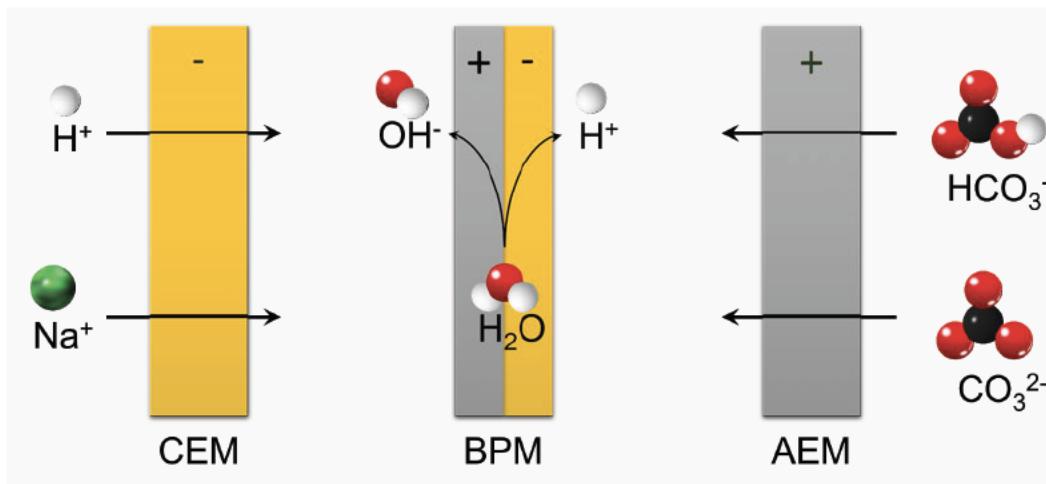


Figure 3 Three different types of ion exchange membranes (IEM), from right to left anion exchange membrane (AEM), which is selective for negatively charged (carbonic) species, bipolar membrane (BPM), which enables fast water dissociation, and cation exchange membrane (CEM), which is selective for positively charged ions. By applying a current, SeaO2's technology separates the dissolved inorganic carbon of the ocean on an ionic level.

The process relies on the pH-sensitive carbonate equilibrium, wherein the bi/carbonate ions ($\text{HCO}_3^-/\text{CO}_3^{2-}$) present in the ocean transform into $\text{CO}_2(\text{aq}) + \text{H}_2\text{CO}_3$ which can then be vacuum stripped and extracted as gaseous CO_2 . The technology enables sustainable pH swings, achieved without the need for additional chemicals, using an electrochemical bipolar membrane electrodialysis (BPMED) stack. The ocean covers more than 70% of the world's surface and absorbs 24% of all CO_2 emissions. Thermodynamically, for every tonne of CO_2 removal, 10000 m³ of seawater needs to be treated (i.e., 4 swimming pools). However, less than 1 % of that volume needs to be filtered and enter the BPMED stack, making the electrochemical oceanic carbon capture a viable Gt-scale CO_2 removal. The capture plants can be situated either on-shore or off-shore or on a moving ship. SeaO2 will work closely with storage companies to permanently remove the captured CO_2 . Any storage company that accepts a liquid or gaseous CO_2 as feed is suitable.

Currently, we are designing our pilot plant of 250 tCO₂/yr capture capacity.

SeaO2's technology features a flow of ocean water passing through the capture plant, which is then treated to remove its carbon dioxide content. This decarbonized water is then returned to the ocean's surface layer where it reacts with the atmospheric CO_2 to absorb an equivalent quantity of the original CO_2 'again'.

SeaO2's electrochemical oceanic carbon capture technology:

- Can be retrofitted as plug-and-play processes in a compact design, which allow small footprints and geometrical flexibility;
- Doesn't need any chemical as the ocean already acts as a massive natural CO₂ absorbent and air contactor
- SeaO2 makes use of standard, already-mature industrial equipment that enable fast paced upscaling of the technology.
- Is energy efficient and fully electrical;
- Can be applied on a large scale.
- Does not require a large land use as it can be mounted on a ship, as a floating plant or offshore on old oil and gas rigs.
- No waste, no byproducts only uses the present ions in the seawater
- Ability to leverage off-peak renewable electricity: We can leverage the fluctuations of the renewable electricity grid: higher production during energy abundance and turning off the production during low hours.
- Electrochemical processes are energy efficient as they can target molecules directly (instead of the medium surrounding them). This means, using our pH-swing method, we can just target the CO₂ molecules and not change anything else about the seawater composition.
- The electrochemical BPMED method is not Capex intensive and has a compact design.
- We do not require external sources of heat or high pressures/vacuum for operation, nor degradation of sorbent material is expected.
- The added advantage of our electrochemical methods is its ability to integrate both CO₂ capture and utilization. This is specially important for the CCU route where green feedstock and fuels can be made by recycling the already emitted CO₂.
- Ocean has ca. 150 times more carbon than the air; the higher the carbon content, the lower amount of volume is needed to reach a capture capacity target.

The main challenge of current CO₂ capture methods is 1) high energy consumption/ costs, 2) high geographic footprint (i.e., need for land), and an 3) unrealistic pathway to gigaton scale carbon capture. There are a few mature CO₂ capture technologies such as absorption, adsorption, membrane separation and cryogenic capture already available in industrial scales. However, 1) these methods often depend on the availability of thermal energy and chemicals which makes them less sustainable, and 2) they are suitable for fuel gas (and not atmospheric CO₂ capture). Finally, the current CCS capacity needs to be increased by 250 times by 2050 (40 Mt/yr to 10 Gt/yr), to reach net-zero in this century. We believe that with our expertise and proven scientific track, we can solve all three challenges.

Our team at SeaO2 comprises a combination of technical and business expertise. We have three co-founders who bring distinct qualifications and experiences:

- Rezvan (Rose) Sharifian, petroleum and chemical engineer with a Ph.D on this technology. specialized in electrochemical CO₂ capture: SeaO₂'s CTO.
- Ruben Brands with legal and business background with established experience in founding startup companies. His background includes business studies from Erasmus University Rotterdam and corporate law from the University of Amsterdam: SeaO₂'s CEO.
- Dr. ir. David A. Vermaas, an associate professor at TU Delft, specializes in electrochemical flow systems, including electrochemical CO₂ capture and conversion. He has extensive experience in scaling up technologies from laboratory scale to the market through startups: SeaO₂'s CSO.

Currently we are a team of 7 and expanding to 10 by the end of 2023. We are located in the country of water management: the Netherlands. Water has always shaped the Netherlands and its people. The Dutch delta has the world's best flood defences. 70% of the Dutch population lives below sea level. That's why the Netherlands has so much expertise in flood control and clean water. That is also why climate mitigation is so high on the agenda of the Netherlands' politics.

Our work has been published in scientific journals over the course of the last four years during Rezvan's Ph.D. Additionally, we have filed a patent through TU Delft to protect the proprietary aspects of our technology. Team SeaO₂ is driven by a shared passion to make a positive impact on climate change and ocean health



Figure 4. SeaO2's team consists of the three founders and the technical team. Currently we are a team of 7 and expanding to 10 by the end of 2023.

We work closely with Dutch knowledge institutes including TU Delft (<https://www.tudelft.nl/>) and Wetsus (<https://www.wetsus.nl/>) and have generated scientific articles on our technology. A few are listed below:

- [1]. R. Sharifian et al., Electrochemical oceanic carbon capture through in-situ carbonate mineralization using bipolar membrane, *Chemical Engineering Journal* 438, 135326 (2022).
- [2]. R. Sharifian et al., Electrochemical carbon dioxide capture to close the carbon cycle, *Energy Environ. Sci.* 14, 781-814 (2021).
- [3]. R. Sharifian et al., Intrinsic bipolar membrane characteristics dominate the effects of flow orientation and external pH-profile on the membrane voltage, *Journal of Membrane Science* 638, 119686 (2021).
- [4]. Diederichsen, K.M., Sharifian, R., et al. Electrochemical methods for carbon dioxide separations. *Nat Rev Methods Primers* 2, 68 (2022).
- [5]R. Sharifian, H.C. van der Wal, R.M. Wagterveld, D.A. Vermaas, Fouling management in oceanic carbon capture via in-situ electrochemical bipolar membrane electrodialysis, *Chemical Engineering Journal*, Volume 458, (2023).

- 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 \$100/t and 0.5Gt targets? What is your approach to quantifying the carbon removed? Please include figures and system schematics and be specific, but concise. Aim for 1000-1500 words.

We are currently designing our pilot plant of 250tCO₂/yr which will be situated on the North Sea shore in the Netherlands. Our 1 tonne prototype is located at Afsluitdijk (Netherlands) at a partner location that generates Blue energy by mixing seawater and freshwater (Figure 5). This partner is experienced in reverse electrodialysis, filtration and building of electrochemical stacks. These factors accelerate SeaO2's technical development rate. We successfully removed our first 5 KG of CO₂ from surface waters using our innovative setup and worked with Paebbl (based in The Netherlands) to mineralize the CO₂ as permanent storage, converting it into solid, valuable rock powder. We have operated more than 240 hr continuous operation using natural water.

For the pilot plant we need 800.000 dollars Capex and expect to fit and build it in two sea containers. We expect ca. 4000 kWh/tCO₂ for electricity usage and will reduce it to close to 3000 kWh/tCO₂ in 2024 by partnering with a water pumping company. We are reviewing different suitable locations (eg. power plants located near the sea shore which are using large amounts of cooling water) in The Netherlands and in negotiations with some of them.

After the pilot plant of 250tCO₂/yr, we will build our 1 ktCO₂/yr capture plant. We design modular compact units that can be stacked up in parallel enabling large scale capture. We design our pilots for long term research and production, continuously upgrading them with improved technology. As we have no plans to decommission them, the pilot lifetime is estimated to be ca. 25 years.

We use commercially available bipolar membranes (BPM) currently. The biggest OPEX part of the electrochemical stack is the voltage that the BPM needs for water dissociation (i.e., more than 0.83 volts per BPM). As the BPM's market grows, the membrane lifetime, resistance and current density improves. Currently the membranes have a lifetime of 3-5 years, and can operate until maximum of 100 mA/cm² in multiple performance cycles. We work closely with membrane manufacturer suppliers

and will improve the materials to have a lifetime of 10-15 years and operate under 500 mA/cm² with lower voltage. Thermodynamically a voltage of 0.4 volts is possible to achieve. These changes in the membrane engineering sector, as well as upscaling the process itself can decrease the total capture costs to \$100/t in 5-7 years.

We can measure the removed CO₂ from the ocean exactly. This is done by performing total dissolved inorganic carbon (TIC) measurements as well as a gas chromatography analysis.

Our overall process is currently at TRL 5, moving into TRL 6. Many subsystems that we use such as filters, pumps, compressors and vacuum pumps are commercially available at TRL 9. Below we represent some visuals from our current 1 tCO₂/yr prototype at Afsluitdijk as well as our recent CO₂ removal which we pressured to 50 Bar and within a CO₂ cylinder, in house. More information is provided on our prototype in the confidential section.

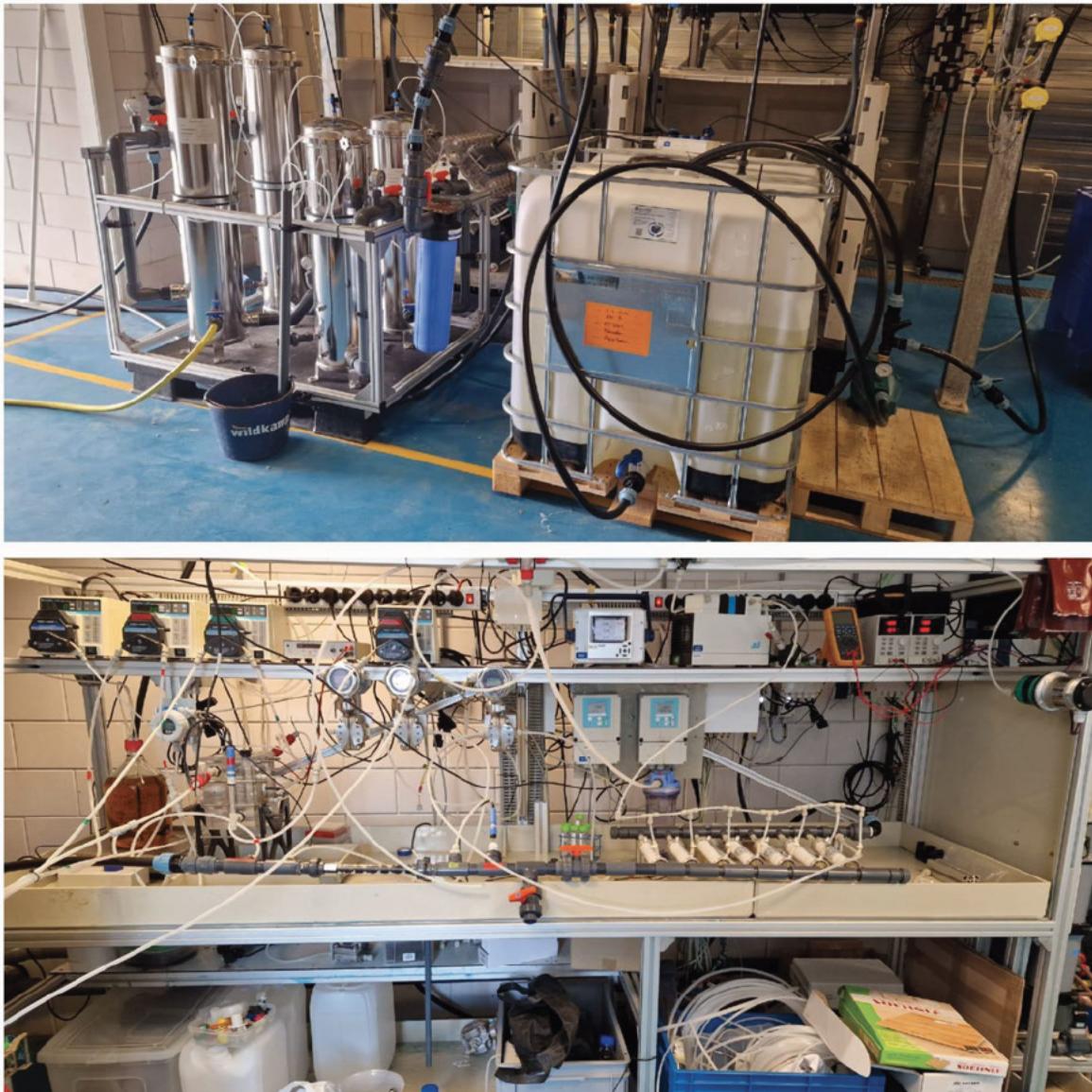


Figure 5 Using our prototype at Afsluitdijk, Netherlands, we successfully removed 5 kg of CO₂ from surface waters using our innovative setup. We are thrilled to announce our partnership with Paebbl, marking the beginning of a collaborative pilot project. This groundbreaking endeavor showcases, to the best of our knowledge, the world's first integrated value chain that captures dissolved CO₂ from the ocean, converts it into a carbonate form through mineralization, and incorporates the resulting mineral mixture as a vital component in concrete production. By partially replacing cement and fine aggregate, this approach offers a sustainable solution. The concrete will be manufactured in the form of standard test blocks. Both startups are located in the Netherlands, making the logistics very convenient and decreasing its footprint. Currently we are evaluating options for bringing our pilot plants close to each other, potentially stripping out compression and transport costs.

We measure the amount of captured/ removed gaseous CO₂ directly; we use a gas flow meter (inline measurement of the CO₂ flow rate in e.g., mln/min) and CO₂ gas analyser (measuring the CO₂ percentage in the captured gas, e.g., ca. 70 %). Therefore, we measure exactly how much CO₂ is removed from the seawater. Subsequently, the removed CO₂ from the ocean will be “replaced” with new CO₂ from the atmosphere to the ocean surface layer. For this part, ocean movement, temperature, wind and geographic location is important to define the kinetics and thermodynamics of the CO₂ absorption. There are adequate scientific literatures present that simulate the CO₂ ocean-atmosphere cycle, its speeds and its extent. We will partner with third parties to exactly measure and monitor this fraction as we operate the pilot. Our current partner, NIOZ <<https://www.nioz.nl/en>> is specialized in monitoring and measuring the changes in the marine ecosystem and will help us in our Monitoring, Reporting & Verification (MRV).

- 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. Aim for 500-1000 words.

Risk	Mitigation Strategy
No contract is yet signed with the water cooling pumping partner that hosts SeaO2's pilot	We have alternative options and are actively looking for opportunities (both in the netherlands and abroad) that can host our pilot as well as the 1000-tonne pilots
Permits to work with (international) water and Ocean health impacts	External advisory expert on the matter and following the procedure on time with the help of partners who have done similar activities before. In the Netherlands, this process is already well under way.
CO ₂ transport and storage partner, including solutions for low quantities under 1 ktCO ₂ /yr	Talking to multiple storage parties, partnering up with other CDR startups that also produce gaseous CO ₂ (g) that needs to be transported/ stored: increasing the delivered CO ₂ (g) volume together. We also welcome suggestions from Frontier
Dependence producer (monopoly) membrane / Price / availability membranes	Partnering with the supplier and looking for other membrane coating enhancement methods

Evidence volume of CO2 captured from the atmosphere, timeline and 1:1 correlation uncertain.	Partnering up with knowledge institute e.g., Wetsus, TU Delft, NIOZ, Wageningen but also external MRV companies
Price and availability renewable electricity	The reduction of energy requirements for our process, combined with a subsidy provided by the Dutch government's energy sector and the global expansion of renewable electricity capacity, will lead to a decrease in this price.
The required hardware for our first pilot e.g., CO2 compressor and vacuum tower has to be custom made because this 250 tCO2/yr pilot has a much larger capacity compared to the lab scale CDR but still a smaller production compared to the already existing industrial (e.g., biogas) instruments	We will work closely with expert engineering firms and have experienced advisory team

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

Proposed CDR over the project lifetime (tons) <i>(should be net volume after taking into account the uncertainty discount proposed in 5c)</i>	500
Delivery window <i>(at what point should Frontier consider your contract complete? Should match 2f)</i>	mid 2024 - mid 2027
Levelized Price (\$/ton CO ₂)* <i>(This is the price per ton of your offer to us for the tonnage described above)</i>	1250 \$/ton CO ₂

* 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).