SeaO2

Carbon Dioxide Removal Purchase Application

Fall 2022

General Application - Prepurchase

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

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

Brief company or organization description

Indirect air capture through electrochemical carbon capture from the ocean, followed by CO2(g) sequestration underground.

1. Project Overview[1]

a. Describe how the proposed technology removes CO_2 from the atmosphere, including as many details as possible. Discuss location(s) and scale. Please include figures and system schematics. Tell us why your system is best-in-class, and how you're differentiated from any other organization working on a similar technology.

- **Introduction**

At SeaO2, we remove CO2(g) from the ocean using electricity and return the decarbonised stream back to the ocean (with only a slightly higher pH than initial). The decarbonized ocean absorbs CO2

[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.

from the atmosphere again as it comes in contact with it, enabling net negative emissions.

- ## Why capture from the ocean/ seawater

The concentration of the (dissolved inorganic) carbon DIC in the ocean is > 140 times higher than the atmosphere, thanks to the vast contact area of the ocean with the atmosphere and its buffering attribute. Due to this higher concentration, the oceanic carbon capture can be more cost efficient than DAC, depending on the plant location/ design. Furthermore, while the land required for DAC competes with the land needed for agriculture, nature and civilization, the ocean capture does not require land (if any), decreasing the geographic footprint of the capture.

Extracting 1 Gton-CO_2 per year (~ 2.7 % of the total global CO_2 emission) from the ocean surface layer (i.e., the upper 100 m) requires processing only a fraction of 0.00025 of this layer's volume. From every 1 L of seawater, approximately 47 mL CO_2 (g) and/ or 208 g $CaCO_3$ (s) can be extracted. When the dissolved inorganic carbon (DIC) content is extracted from the ocean, the decarbonized stream can be directed back to the ocean where it can re-equilibrate with the atmosphere again through absorbing CO_2(g) from the atmosphere, allowing the cycle to be repeated. The extracted carbon from the ocean results in indirect carbon capture from the atmosphere 1:1. Such re-equilibrium is re-reached within 1 year.

Considering the ocean absorbs a quarter of the total carbon dioxide emissions, and considering that 71 % of the world is contained with water, oceanic carbon capture has the potential for GtC scale CDR. Furthermore, the combination of oceanic CDR with offshore wind farms is an added advantage both with regards to the geographic and energy footprint of the capture process.

- ## How does the method work?

In our electrochemical method, to capture the carbon, a membrane-based electrochemical method is used [1-4], where only seawater and electricity are needed as input (Figure 1).

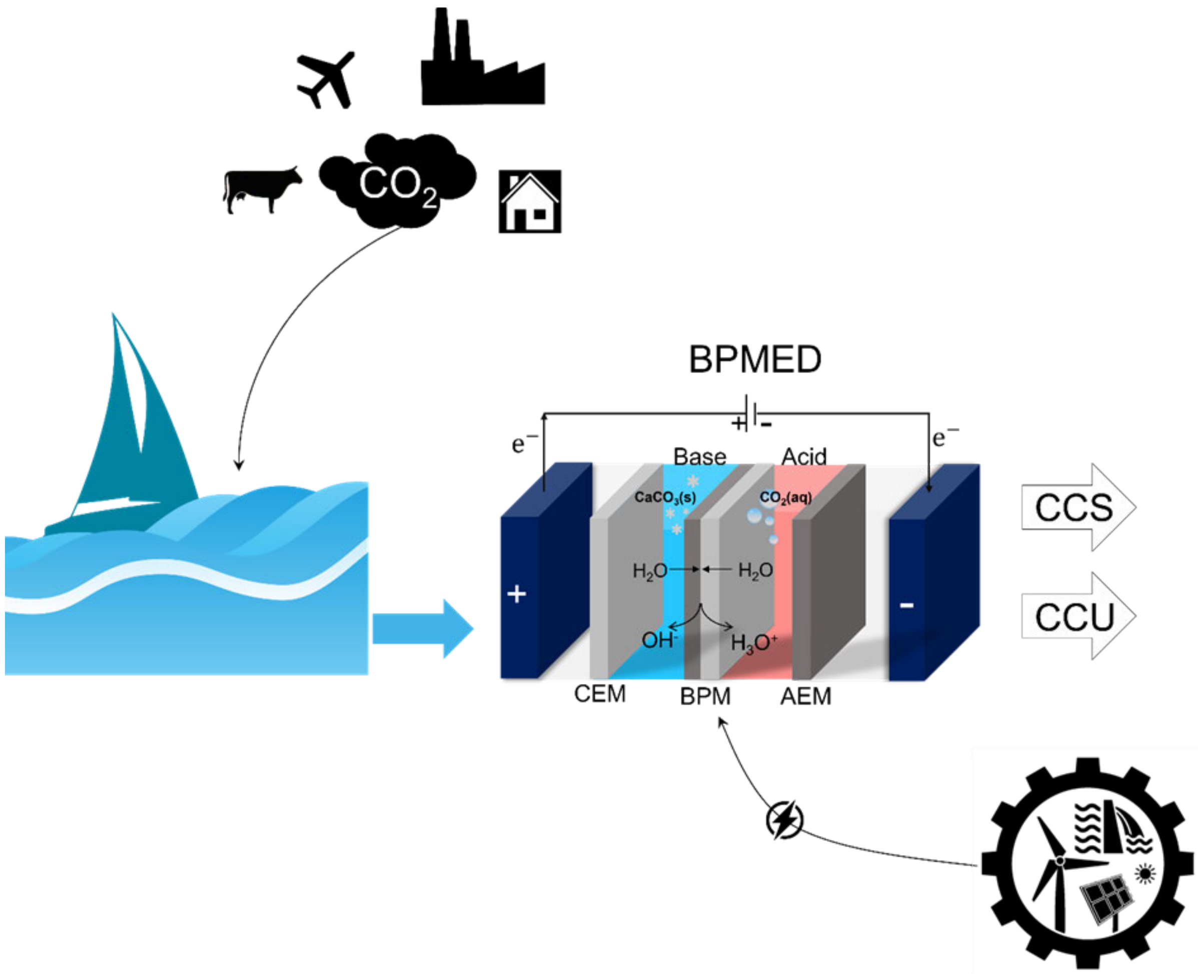


Figure 1 The electrochemical bipolar membrane electrodialysis (BPMED) stack technology for sustainable carbon capture from the ocean and the possible captured carbon fates of utilization (CCU) or storage (CCS). The BPMED cell consists of two end electrodes, cation/ anion exchange membranes (CEM, AEM) and the bipolar membrane (BPM, where the water dissociation reaction (WDR) takes place). Gaseous CO2(g) and solid CaCO3(s) are the captured products from the acid and base compartments, respectively that can be used or stored.

The concept is based on changing the seawater pH and thus shifting the carbonate equilibrium of the ocean to change its dissolved carbon (in form of bicarbonate ions) to either gaseous CO2 (g) (through acidification) or solid calcium carbonate (through alkalinization), Figure 2. The decarbonized ocean can have a (slightly) higher pH than initial seawater, promoting further CO2 (g) absorption from the atmosphere. The pH is adjusted by using the bipolar membranes and can be controlled by the amount of applied current and seawater flow rate. We will use the process as shown in Figure 2A in this proposal. The process shown in Figure 2B is best to be combined with membrane based desalination units or other industries where produced acid can be used in.

The innovation in our technology is using an electrochemical method to produce the required pH-swing (i.e., acid and base production) for carbon capture (Figure 2). Electrochemical CO2 capture technologies are flexible, can address decentralized emissions (e.g., ocean and atmosphere), and fit in an electrified industry. They have the potential to be energy efficient as they can target molecules directly (instead of the medium surrounding them).

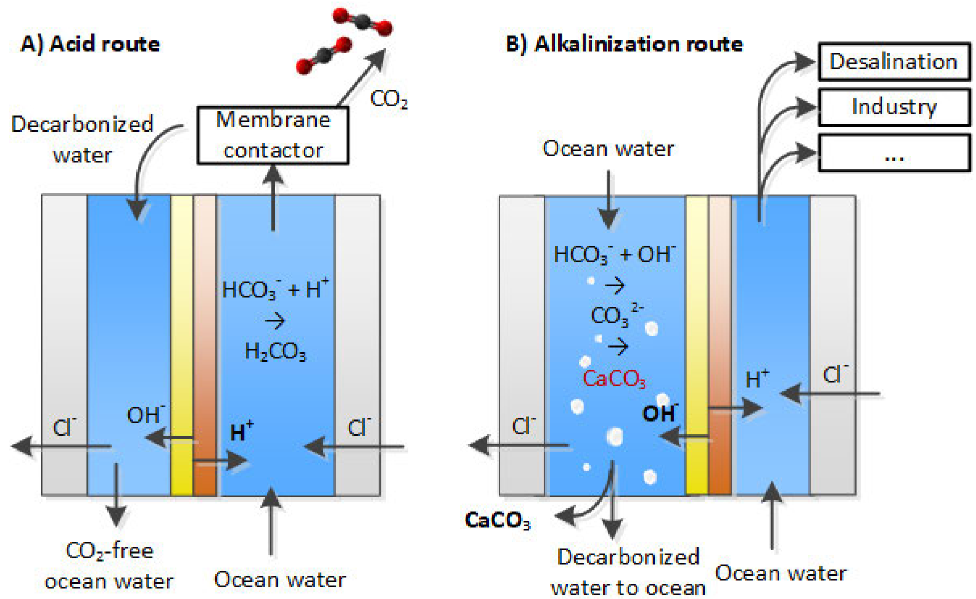


Figure 2 Concept of CO_2 capture from the ocean water via electrochemical pH-swing. A) CO_2 release using an acid route. B) CO_2 mineralization using alkalinization route. The water dissociation is facilitated via the bipolar membrane (BPM) upon application of electricity.

The capture plant can be stand alone or co-planted (with e.g., desalination plants). It can be onshore and/ or offshore. The costs are the lowest if the capture unit is co-planted or if it floats in the ocean (stand alone or e.g., on a ship).

- ## Current state of the technology

Currently, all electrochemical carbon capture methods have a TRL < 5. To bring this technology to the market, in addition to increasing the TRL of the carbon capture step, CO2 (g) transport and storage (i.e., underground) partners should be involved. Furthermore, Monitoring, reporting, and verifying (MRV) of the removed/stored carbon and its effect on ocean life should be studied in parallel. All three criterias are on our list. We are already talking with potential storage companies, MRV partners and we are actively running experiments (also using real seawater) in our R&D labs.

- ## The advantage of our technology

Capturing carbon from the ocean removes the need for a large absorption tower (as it is otherwise customary in direct air capture DAC e.g., using amine-based capture), because the natural ocean-atmosphere contact area acts as a massive absorption tower. The oceanic CDR unit can be placed on a boat, floating or mounted on an (old) oil/gas offshore platform, reducing/ eliminating the required land needed for CDR. Considering the competition for land for agriculture and housing, this is a great plus compared to land-based capture locations. Furthermore, combination with an offshore oil/gas platform that is connected to an empty reservoir enables direct CO2(g) sequestration, eliminating the cost for CO2(g) transport or above-ground storage.

The process parameters within the stack can be controlled to adjust the final pH of the decarbonized seawater stream; while it is possible to create the outflow with a pH like that initial of the ocean (pH 8.2), it is also possible to enhance ocean alkalinity. If so, in addition to ocean CDR, ocean alkalinity is enhanced which is beneficial for oceanic corrals and carbonate using organisms.

This method only requires electricity and seawater as input and uses the already commercialized membranes, electrodes, and stack. No harmful chemicals are needed, and the process is performed in ambient temperature and pressure, reducing the cost and complications of a large-scale plant.

- **Scale and timeline**

We can demonstrate a 1KtCO2/yr capture capacity plant in 3 years. In 2023, we aim for 250 tCO2/yr capacity (this proposal). To increase the capture capacity, we simply need to add (i.e., copy and paste) electrochemical stacks (or plants location for Gt scale). Within the stacks, there are many membranes (even up to 200 m2), but these are bundled in series, resulting in a rather small stack (Figure 3 as an example).

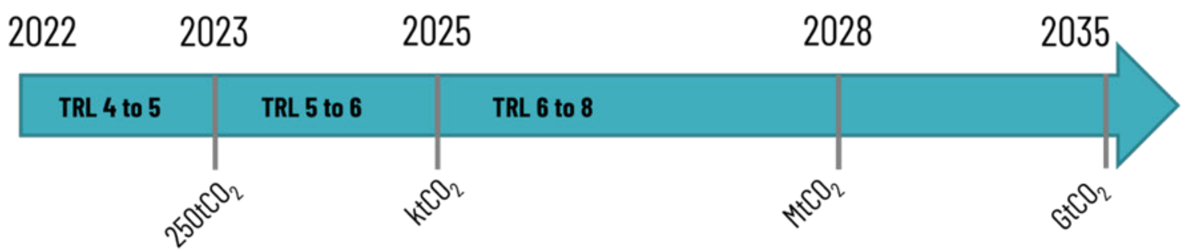


Figure 3 SeaO2 carbon capture timeline

In the big picture, going from our current prototype (Figure 4) to the desired stack for 1KtCO2/yr capture, means upscaling in the order of 20000 times (from the current prototype). This requires a budget of 750,000-1,500,000 USD and takes ca. 3 years. Due to confidentiality, we cannot share a photo of the designed prototype but are happy to provide more information within a small online group.

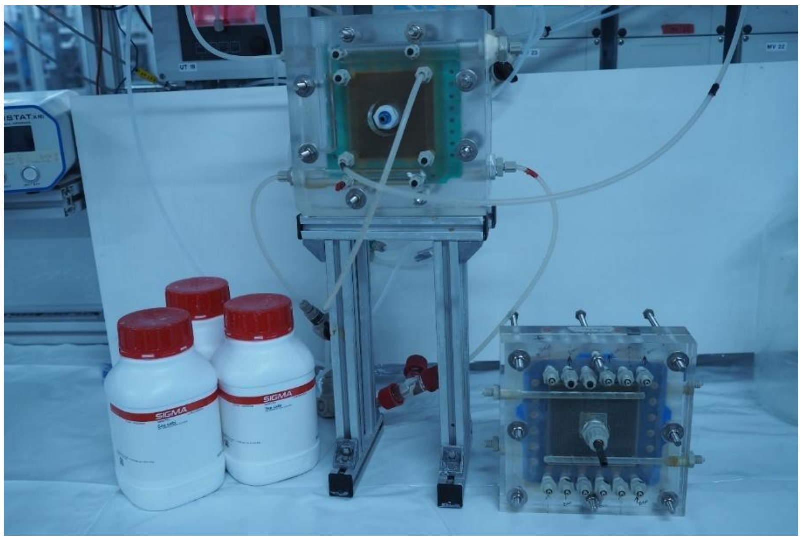


Figure 4 The 100 cm^2 electrochemical stack prototypes. See our article [1] for more information on the prototype.

- **Why us: what makes us a strong team?**

Our core team consists of both business , technical and science experts. We are 3 co-founders, from which 2 are working full-time on SeaO2 now. The team (*Figure 9*) is as follows:

(1) ir. Rezvan Sharifian (graduated PhD at TU Delft university in the Netherlands). Chemical and petroleum engineering background, specialized in electrochemical oceanic carbon capture during the last 4 years through the PhD project. Working full-time on SeaO2 for technical development.

(2) MBA & LL.M Ruben Brands, true expert in creating start-up companies, with both business (Erasmus University Rotterdam) and corporate law (University of Amsterdam) expertise. Working full-time on SeaO2.

(3) Dr. ir. David. A. Vermaas, TU Delft Associate professor, specialized in electrochemical flow systems including CO2 capture/ conversion and experienced in upscaling technologies from lab scale into the market through start-ups. Strategic advisor and co-founder SeaO2.

- **References (a few of our own team work: see the articles provided in our "scientific articles" folder)**

[1]. R. Sharifian et a.l, 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).

b. What is the current technology readiness level (TRL)? Please include performance and stability data that you've already generated (including at what scale) to substantiate the status of your tech.

We are at TRL 4, and we already have a prototype (100 cm2 stack, figure 4, that has successfully extracted oceanic carbon as $CaCO_3$ [1]). With our expertise on the subject, we are increasing our TRL to TRL 5 (enabling 250 tCO_2/yr already in 2023) and to TRL to 6 (enabling ktCO_2/yr scale carbon capture in 3 years).

Even Though so far we mainly have focused our research on oceanic carbon extraction by $CaCO_3$ production from seawater, for the large scale capture plant we choose for the acid-route (Figure 2A). The stack design remains the same, the only difference is that the product of capture using the acid route is gaseous CO_2(g) (and thus not solid $CaCo_3$(s)). The stack parameters (flow rate, size, current density etcFigure 5) remain the same. We are looking for underground storage partners at the moment. Thankfully, the port of Rotterdam in the Netherlands is very active in this area and we see a great potential for collaboration there.

As for the performance and stability data: In our latest work, through in situ mineralization enabled using bipolar membranes, Aragonite (polymorph of $CaCO_3$) was extracted from (real and synthetic) seawater as an ocean carbon removal strategy. By controlling the current density and cell residence time, >60 % of the dissolved inorganic carbon (DIC) and ≥ 16 % of the calcium ion is extracted, without the need for any additional chemicals. An energy consumption of 0.88 kWh/kg $CaCO_3$ is obtained for DIC-capture from real seawater with $CaCO_3$ production rate of 0.64 kg $CaCO_3$/ h m2. Theoretically, at a mild-pH swing (e.g., base pH 10.0 and acid pH 4.5, thus ΔpH = 5.5) the thermodynamic energy required to capture $CaCO_3$ though in situ mineralization is ~ 35 kJ/mol $CaCO_3$ which is <10 % of that experimentally achieved (Figure 6). However, the irreversible BPM-overpotential is responsible for > 55 % of the required electrical energy. We have seen that focusing on membrane engineering to achieve fast WDR kinetics in the BPM, with highly permselective ion-exchange layers to exclude co-ions, and with optimum thickness of the layers is the most effective way to minimize energy losses. The process remains stable. The only limitation is the possible membrane fouling (which we have successfully removed) and its lifetime (3-5 years).

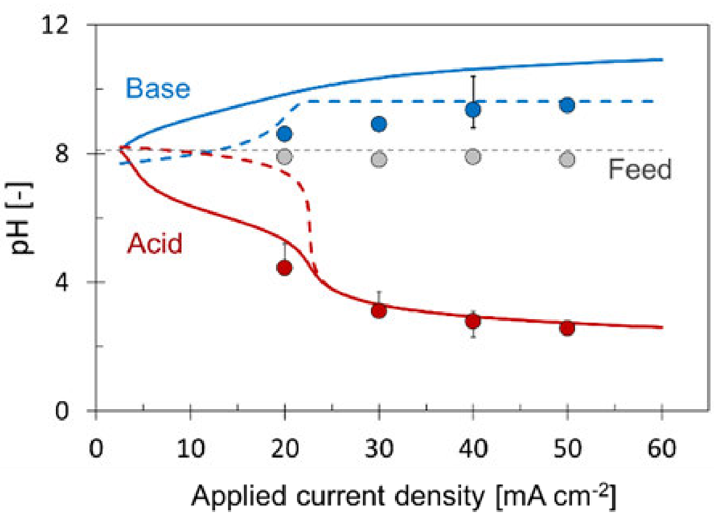


Figure 5 Comparison of the simulated (lines) and experimentally obtained values (bullets) at each applied current density. Dashed lines show the (simulated) pH-change after DIC-extraction as $CO_2(g)$ (red) and $CaCO_3(s)$ (blue)

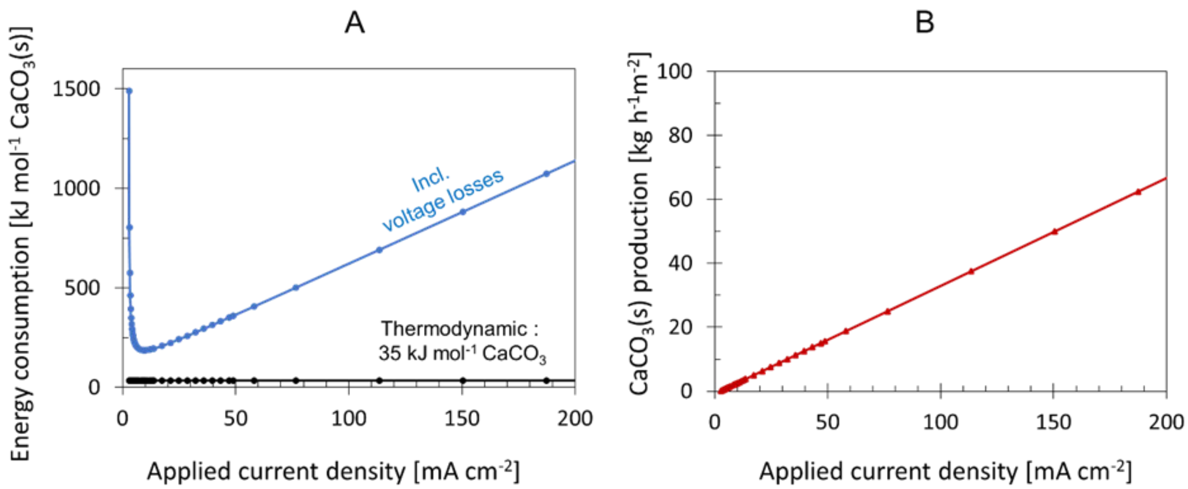


Figure 6 Relation between the applied current density vs. (A) electrical energy consumption and (B) calcium carbonate normalized production rate. Simulations are done assuming a 10×10 cm2 BPM-CEM cell containing 10 cell pairs and base-pH 10.0 (i.e., produced OH- ions of 0.0023 M). The value of the thermodynamic limit is obtained using the minimal membrane voltage for required ΔpH = 5.5.

c. What are the key performance parameters that differentiate your technology (e.g. energy intensity, reaction kinetics, cycle time, volume per X, quality of Y output)? What is your current measured value and what value are you assuming in your nth-of-a-kind (NOAK) TEA?

Key performance parameter	**Current observed value (units)**	**Value assumed in NOAK TEA (units)**	**Why is it feasible to reach the NOAK value?**
Carbon capture efficiency	60 %	90 %	Better membrane contactors enhanced within our startup
Current density	5-50 mA/cm2	100 mA/cm2	Has been shown possible for similar membranes within milk and batteries industry
Carbon capture rate	Grams of carbon removed	GtCO2/yr scale	Simulations shown that to be possible, especially seeing the great potential the ocean has
Electrical energy consumption (BPMED)	2000 kWh/tCO2 at current density <20 mA/cm2	1200-1300 kWh/tCO2 at current density >60 mA/cm2	Simulations showed this possible. Membrane engineering and an improved stack design are required to decrease the ohmic losses within the stack
Pumping energy consumption	400 kWh/tCO2 in a small lab scale	<1000 kWh/tCO2 in the final design	Estimation shows the electrochemical stack would need at

			least ca. 1200-1300 kWh/tCO2 (for an industrial scale). The rest is the pumping energy, which can be ca. 4500-100 kWh/tCO2, depending on the plant location/ design, a stand alone plant needs the largest amount of pumping electricity, while co-planting with a desalination plant or water cooling plant can reduce the pumping costs drastically.
Membranes lifetime/ performance	3 yrs, with 95 % performance	>10 yrs, with 95 % performance	Charged membrane engineering and research is ongoing and have already shown lots of improvements in the past 10 yrs
Faradaic efficiency (FE)	90 % at current density <20 mA/cm2	95 % at current density >60 mA/cm2	Charged membrane engineering and research is ongoing and have already shown lots of improvements in the past 10 yrs
Bipolar membrane (BPM) voltage for acid/base production	>0.83 V at current density <20 mA/cm2	<0.3 V at current density >60 mA/cm2	Thermodynamically possible. Requires catalyst and membrane engineering

d. Who are the key people at your company who will be working on this? What experience do they have with relevant technology and project development? What skills do you not yet have on the team today that you are most urgently looking to recruit?

We have 1 scientist, 1 engineer with PhD and 1 expert in business development and strategy in our core-team of founders.

We are partnering with marine biologists for ocean life analysis. We will be working with a mechanical engineer and automation engineer later this year. For technical development we need a process engineer, membrane material specialist, LCA / TEA specialist and more lab engineers (for scaling up builds). Right now, we work with some of the above on a freelance basis, but the best will be to have them onboard. We can progress on a freelance basis but to reach our Mt scale in 2028, we need a team expansion for fast achievement (In the TEA, we assumed 20 full time employees for MtCO2/yr capacity and 4 full time employees for the KtCO2/yr capacity, in addition to the 3 co-founders).

We will expand our commercial team as well, after the pilot phase is done.

e. Are there other organizations you're partnering with on this project (or need to partner with in order to be successful)? If so, list who they are, what their role in the project is, and their level of commitment (e.g., confirmed project partner, discussing potential collaboration, yet to be approached, etc.).

Partner	Role in the Project	Level of Commitment

CO_2 underground storage	Injecting CO_2 underground for storage	Discussing potential collaboration
CO_2 transport	(green) transportation of CO_2 from capture plant to storage site	yet to be approached
Marine ecosystem monitoring	Monitoring and measuring the long term effect of our method on ocean life	discussing potential collaboration (NIOZ)
TU Delft university of technology	Providing scientific advice and performing LCA/ TEA assessment in collaboration with research group	confirmed project partner (shareholder in our startup)
Stack and membrane supplier	Provider for the electrochemical stack and the charged membranes	discussing potential collaboration
Rijkswaterstaat	responsible for the design, construction, management and maintenance of the main infrastructure facilities in the Netherlands: permits to use seawater	Joining startup program
Green energy supplier	We will need a large amount of renewable electricity (ca. 2500-6000 kwh/tCO_2) with affordable price	In talks with RVO and Dutch government
Monitoring, reporting and verifying (MRV)	Monitoring, reporting and verifying our capture method	discussing potential collaboration (NIOZ, Wageningen university)

f. What is the total timeline of your proposal from start of development to end of CDR delivery? If you're building a facility that will be decommissioned, when will that happen?

> For 250tCO_2/yr: we finish the detailed engineering/ stack design by Q1-2023, stak/ membrane delivery Q2-2023, site preparation Q3-2023, start capture Q4-2023, CDR-delivery in Q4-2024 (ca. 720 kgCO_2/d).

g. When will CDR occur (start and end dates)? If CDR does not occur uniformly over that time period, describe the distribution of CDR over time. Please include the academic publications, field trial data, or other materials you use to substantiate this distribution.

> CDR is distributed over time. Starting 1st October 2023, with a capacity of 720 kgCO_2/d removal. Assuming 24 hr/d production with 350 d/yr, this translates into 250 tCO_2/yr removal from the ocean. The final day of production will be in Q4-2024. The 250tCO_2/yr capture is the gross capacity (222 tCO_2/yr). This 250tCO_2/yr amount will be removed 1:1 from the atmosphere; the re-equilibration between the atmosphere and ocean will take around 1 year.
>
> Thanks to the nature of our technology, the capacity can be adjusted easily (+/- 50 tCO_2/yr): e.g., higher production in warmer periods of the year with lower production with colder months to for

example adjust for renewable electricity availability.

The applied current density and flow rate of the method control the final CDR rate: higher current density, enables higher energy available for pH-swing [1-4], enabling a higher volume of the seawater/ ocean to be treated for CDR. The stack can even be turned off easily (for example for membrane washing).

The increase in the capacity is enabled by stacking up more stacks of the same design/ size and thus goes fast.

h. Please estimate your gross CDR capacity over the coming years (your total capacity, not just for this proposal).

Year	Estimated gross CDR capacity (tonnes)
2023	50 tCO_2
2024	250 tCO_2
2025	750 tCO_2
2026	1KtCO_2
2027	100KtCO_2
2028	1MtCO_2
2029	5 MtCO_2
2030	10 MtCO_2

i. List and describe at least three key milestones for this project (including prior to when CDR starts), that are needed to achieve the amount of CDR over the proposed timeline.

	Milestone description	Target completion date (eg Q4 2024)
1	PFD and P&ID completion	Q4-2022
2	Plant location agreement (in collaboration)	Q4-2022
3	Site preparation incl. electrochemical stack (incl. membranes) and equipment delivery for the 250 tCO_2/yr capacity plant	Q1 & Q2-2023
4	Stack and filtration unit assembly	Q3-2023
5	Storage/ transport partner agreement	Q2-2023

j. What is your IP strategy? Please link to relevant patents, pending or granted, that are available publicly (if applicable).

> We have filed for a patent on 18-03-2022 with the title "Carbon Capture and Conversion". The patent rights are for TU Delft (the university where the PhD took place). However, TU Delft has granted permission to use the patent, exclusively in a specific field of use, for a start-up under the shareholder agreement document that we are now finalizing with TU delft.

k. How are you going to finance this project?

> For the 250 tCO_2/yr we will need ca. 300,000 $ Capex and 900,000 $ Opex (from which ca. 650,000 $ is for electricity costs of ca. 3650 kWh/tCO_2). We do plan to decrease our total electricity consumption to < 2500 kWh/tCO_2 as we increase the CDR capacity, but for now the capture energy consumption is high.
>
> We can finance the capex via dutch subsidies/ grants. For the rest we need to enter European subsidy financing. We also hope to generate revenue from pre-purchase agreements. We don't plan to enter investment rounds for the 250 tCO_2/yr prototype at the moment.
>
> For the total project costs, the price and availability of renewable electricity, the price of the membranes and their lifetime are crucial. Thankfully, the renewable electricity capacity is increasing while its price is expected to decrease.

l. Do you have other CDR buyers for this project? If so, please describe the anticipated purchase volume and level of commitment (e.g., contract signed, in active discussions, to be approached, etc.).

> Not yet. But we have approached Ledgy, Southpole/NextGen, Carbon Direct Supplier (via Xprize "60" cohort)

m. What other revenue streams are you expecting from this project (if applicable)? Include the source of revenue and anticipated amount. Examples could include tax credits and co-products.

> We aim to sell carbon credits for the 250 tCO_2/yr project.

n. Identify risks for this project and how you will mitigate them. Include technical, project execution, ecosystem, financial, and any other risks.

Risk	Mitigation Strategy
Permits to work with (international) water	External advisory expert on the matter and following the procedure on time with the help of partners who have done similar activities before.
Finding a CO2 storage partner that is willing to sequester low volumes of ca. 100tCO2	Talking to multiple storage parties, partnering up with other CDR startups that also produce gaseous CO2(g) that needs to be stored: increasing the delivered CO2(g) volume together
Dependence producer (monopoly) membrane / Price / availability membranes	Partnering with the supplier and looking for other suitable alternatives
Finding well-trained personnel (Design membrane stack)	Actively looking on time, use free-lancers and expert (who might even be with retirement)
Regulations on ocean / biodiversity	External advisory expert on the matter and following the procedure on time with the help of partners who have done similar activities before. Partnering up with knowledge institute e,g,, Wetsus, TU Delft university of technology, NIOZ
Need for funding	Dutch and european grants, pre-purchase agreements, look for small scale markets to use the captured CO2
Evidence volume of CO2 captured from the atmosphere, timeline uncertain.	Partnering up with knowledge institute e,g,, Wetsus, TU Delft, NIOZ, Wageningen but also external MRV companies
Price and availability renewable electricity	Subsidy from dutch government energy section, plus the global increase in the renewable electricity capacity
Competing scientists in the same field who are also setting up a startup based on comparable technology	To mitigate climate change, we need all possible actions to be taken. We believe in collaboration and partnership and not competition, especially as the CDR market is so high in demand while the supply is little. In less than 8 years, the CDR capacity should increase to 4 GtCO2/yr while now it is only 40 MtCO2/yr!
(insurmountable) challenges in scaling technology	Hiring experienced engineers, learning from the past projects
Sufficient supply, lower cost and lifetime of bipolar membranes	External membrane engineering and development in the membrane research

2. Durability

a. Describe how your approach results in permanent CDR (> 1,000 years). Include citations to scientific/technical literature supporting your argument. What are the upper and lower bounds on your durability estimate?

> We capture oceanic Carbon as gaseous $CO_2(g)$. The $CO_2(g)$ will then be transported and sequestrated in underground empty oil/gas/ aquifer/ salt reservoirs or in e.g., basalt rocks (forming CO_2 to form stable carbonate minerals). Aside from the risks of leakages, the storage is permanent. However, we do notice contradictory information with regards to the potentials and risks of underground CO_2 storage. We hope that as our capture technology develops, the storage also develops further, with more data available.
>
> At this point, we are talking to potential storage partners to gather more data on costs/ boundaries. TU Delft university of technology (TU Delft) is a shareholder in our startup and we will perform more research on the best geological storage option together with them.
>
> We are aware that only knowing the available storage volume says too little about how much CO_2 could actually be sequestered in a specific location. We also know that "the planning of a CCS investment requires the rate of CO_2 injection into a secure reservoir to match the rate of supply from associated facilities that have CO_2-capture technology installed. If the planned injection rate cannot be sustained for the full life of those investments, then an unplanned emission of CO_2 will occur in the future. Understanding that timespan is crucial, and a meaningful expression of storage capacity requires the explicit pairing of two separate terms: a sustainable rate of injection for a defined period of time" [5]. We will continue our discussions and research on geological storage to avoid mistakes, but at this point we need to gain more insight on the matter.
>
> [5] Lane, J., Greig, C. & Garnett, A. Uncertain storage prospects create a conundrum for carbon capture and storage ambitions. Nat. Clim. Chang. 11, 925–936 (2021) https://doi-org.tudelft.idm.oclc.org/10.1038/s41558-021-01175-7

b. What durability risks does your project face? Are there physical risks (e.g. leakage, decomposition and decay, damage, etc.)? Are there socioeconomic risks (e.g. mismanagement of storage, decision to consume or combust derived products, etc.)? What fundamental uncertainties exist about the underlying technological or biological process?

> Physical risks involved with $CO_2(g)$ leakage back to the surface. Upon injection of the CO_2 into the underground storage, the fraction of the CO_2 that would be stored depends on both the physical and geochemical trapping mechanisms. Thankfully, there are many uncertainty analyses of underground CO_2 Storage already done (Figure 7), that we can benefit from.

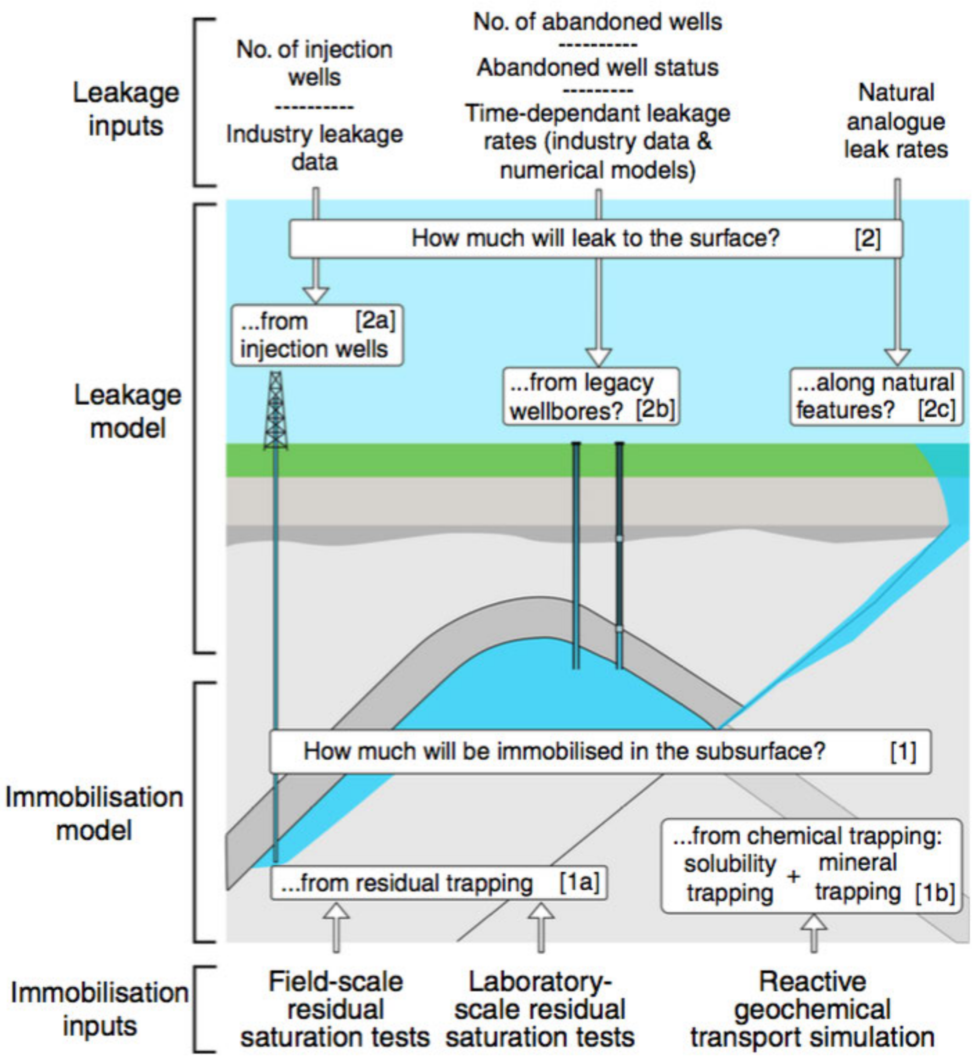


Figure 7 Schematic diagram showing the leakage inputs (i.e., all the ways it could escape back into the atmosphere) and immobilization inputs (all the ways of permanently trapping it underground) considered in the Storage Security Calculator model. Source: Alcalde et al. (2018)

The three ways that CO2 could become permanently trapped underground include residual trapping, when CO2 gets trapped in the small gaps between rocks; solubility trapping, which occurs when CO2 dissolves in water; and mineral trapping, the conversion of CO2 into solid minerals. The mineral trapping has the lowest risks because as the CO2 becomes a rock – it's never going to come back to the surface. This is possible at a storage site at Reykjanes peninsula, Iceland. Thankfully, being located in the Netherlands, we can deliver our captured CO2 to the port of Rotterdam, from where it can then be shipped to Reykjavík where it will be transported by truck to the storage site at Reykjanes peninsula

3. Gross Removal & Life Cycle Analysis (LCA)

a. How much GROSS CDR will occur over this project's timeline? All tonnage should be described in **metric tonnes** of CO_2 here and throughout the application. Tell us how you calculated this value (i.e., show your work). If you have uncertainties in the amount of gross CDR, tell us where they come from.

Gross tonnes of CDR over project lifetime	250 tCO2/yr gross (11% emission meaning 222 tCO2/yr net)
Describe how you calculated that value	We ran an initial LCA using cif_CLIMPACT FORECAST database assuming a gross capture of 1000 tCO2/yr. We are aware that we need to improve our LCA by further detailed calculations in the future and that is on our short term to-do lists. The report is provided as supplementary info. The LCA is only for the capture part (i.e., the electrochemical stack and equipment). The transportation of the underground storage is excluded, but we will include it in our more detailed LCA (begin 2023). We used the following Assumptions Production: -We use green electricity (6000 kwh/tCO2 for a stand alone unit). We will use offshore wind because of our own location (near sea shore or installed on (old) gas drilling platform) and possible geological storage options are: oil and gas reservoirs. -electrodes used are Titanium: assuming titanium density of 4.5 grams per cm3, and 2 electrodes of 100*100*1 cm3, we need 45 kG for 1200 tCO2, which means 0.0375 kG/tCO2. To allow error margins, Wwe assume \50KG per 1200 ton CO2 (elektrode cell) = 0,04216666 KG per ton of CO2 -membranes used are similar to Nafion: Assuming Nafion density of 1.58 g/cm3 , and assuming we need 202 membranes with dimensions of 100*100*0.013 cm3, we need 41.5 KG Nafion for 1200 tCO2. This translates into 0.035 We assume 100KG Nafion per 1200 ton CO2 = 0,0833333 KG per ton of CO2 -Steel: Assuming steel density of 7.85 g/cm3, and assuming we need 50*50*50 cm3 steel for capturing 1200 tCO2, we need 0.82 KG steel for 1 tCO2. -stack is made of PMMA: Polymethyl Methacrylate: The stack itself will be made of PMMA. Assuming 1.18 g/cm^3 density for PMMA, and 2 end plates of 120*120*20 cm3, we will need 680 kg for 1200 tCO2, meaning 0.57 kg/tCO2. -required PCB = Printed Circuit Board (including IC's): we don't have a calculated number for PCB used per tCO2 yet, so we over estimated assuming for the 1200 tCO2, we would need 24 KG PCB (500 g per device, incorporated in 48 devices), which translates into 20 G per tCO2. -tubing and pipes: PET Bottle Grade:We need PVC and PET tubing. assuming 1.38 g/cm^3 density for PET, and assuming we need 34 liter pipes material (assumed for 15 m pipes/tubes with wall thickness of 2

	cm), we need ca. 47 KG PET for 1200 tCO2 which means 0.04 KG PET/tCO2. to allow an error margin, we assumed 0.042 -Transportation: We have here assumed (the best case scenario) of mounting our capture plant on an old oil/gas offshore rig, where CO2 can be stored directly after capture, underneath the rig, inside the empty reservoir. We are aware that this is an ideal state, in our future/ detailed LCA we will consider the effect of transport via trucks and ships (e.g., assuming we will deliver the captured CO2 to the port of Rotterdam and from there ship it to Iceland, followed by trucks to Carbfix storage location).

b. How many tonnes of CO_2 have you captured and stored to date? If relevant to your technology (e.g., DAC), please list captured and stored tons separately.

Less than 1kgCO2/yr captured Nothing stored

c. If applicable, list any avoided emissions that result from your project. For carbon mineralization in concrete production, for example, removal would be the CO_2 utilized in concrete production and avoided emissions would be the emissions reductions associated with traditional concrete production. Do <u>not</u> include this number in your gross or net CDR calculations; it's just to help us understand potential co-benefits of your approach.

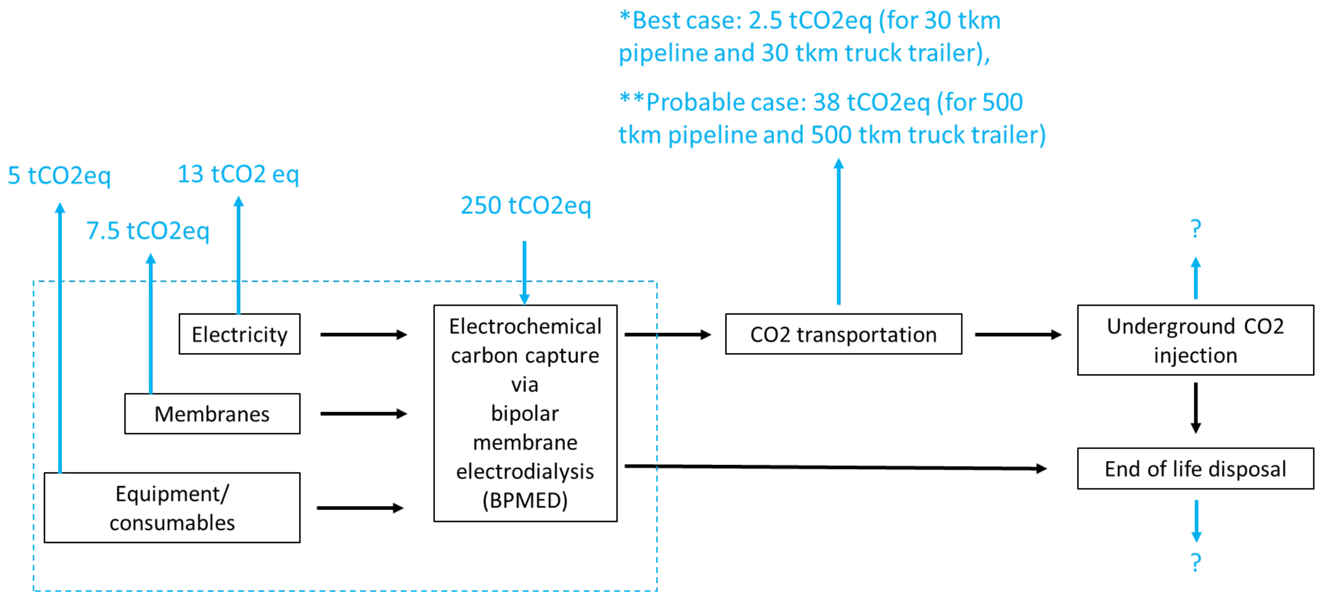
We remove CO2 indirectly from air, through direct ocean capture.

d. How many GROSS EMISSIONS will occur over the project lifetime? Divide that value by the gross CDR to get the emissions / removal ratio. Subtract it from the gross CDR to get the net CDR for this project.

Gross project emissions over the project timeline *(should correspond to the boundary conditions described below this table)*	250 ton/CO2
Emissions / removal ratio *(gross project emissions / gross CDR–must be less than one for net-negative CDR systems)*	28 ton/CO2
Net CDR over the project timeline *(gross CDR - gross project emissions)*	222 ton/CO2

e. Provide a process flow diagram (PFD) for your CDR solution, visualizing the project emissions numbers above. This diagram provides the basis for your life cycle analysis (LCA). Some notes:

- If you've had a third-party LCA performed, please link to it.



*) The whole project results in 89 %net CO2 capture (excl. storage/ end of life disposal)
**) The whole project results in 75.5% net CO2 capture (excl. storage/ end of life disposal)

f. Please articulate and justify the boundary conditions you assumed above: why do your calculations and diagram include or exclude different components of your system?

We have run the LCA for a 1000 tCO2 capacity plant. Assuming linear relation, we have interpolated the values for a 250 tCO2/yr plant. Our system consists of 4 boundaries:

1. The capture plant (The electrochemical stack, charged membranes, the equipment/consumables within and the electricity needed for the stack).
2. Transportation of the captured CO2
3. underground sequestration
4. End of life disposal

The data for the first 2 options are shown here (based on the CIF-Impact forecast database). The underground sequestration and end of life disposal are important, but we don't have a number for them yet. We will improve our LCA and will have these numbers by Q2-2023.

For the capture plants, the following numbers are assumed (explained in table above).

Production	$kgCO_2eq.$	quantity per 1 ton of CO2		$kgCO_2eq.$ per 1 ton of CO2
+ Electricity from offshore (5MW, capacity factor (	0.00226 per MJ	21600	MJ	48.88
+ TiAl6V4	46.88 per kg	0,042	kg	1.969
+ Nafion	831 per kg	0,035	kg	29.09
+ Steel (21% sec = trade mix average) EU	0.9576 per kg	0,82	kg	0.7852
+ PMMA (Polymethyl methacrylate)	3.75 per kg	0,57	kg	2.137
+ drinking water europe*	0.00064 per kg	3500	kg	2.223
− Carbon Dioxide capture	1 per KG CO2	1000	KG CO	-1000
+ PCB = Printed Circuit Board (including ICs)	475 per kg	20	g	9.5
+ PET bottle grade	2.19 per kg	0,042	kg	0.09198

The origin of electricity is the most uncertain/ risky parameter here. We chose offshore wind electricity that has a very low carbon footprint compared to the industrial grid. As (ultimately) we will be located close to the sea or on an offshore platform, this is a reasonable choice. However, we are sure that this is the ideal/ best case scenario in our initial LCA.

As for the transportation, We have here assumed (the best case scenario) of mounting our capture plant on an old oil/gas offshore rig, where CO2 can be stored directly after capture, underneath the rig, inside the empty reservoir. We are aware that this is an ideal state, therefore, we also have considered a probable case of 500 tkm truck plus 500 tkm pipeline length. Both numbers are shown. The higher tkm results in higher emission of CO2, thus lower net CO2 capture (75.5 % instead of 89 %).

g. Please justify all numbers used to assign emissions to each process step depicted in your diagram above. Are they solely modeled or have you measured them directly? Have they been independently measured? Your answers can include references to peer-reviewed publications, e.g. Climeworks' LCA paper.

Process Step	**CO_2(eq) emissions over the project lifetime (metric tonnes)**	**Describe how you calculated that number. Include references where appropriate.**
Electricity	13 tCO2	48.88 kg/tCO2 × 250 tCO2 (rounded up)
Membranes	7.5 tCO2	29.09 kg/tCO2 × 250 tCO2 (rounded up)
equipment/ consumables	5 tCO2	20 kg/tCO2× 250 tCO2
BPMED capture unit	250 tCO2	Controlled by the amount of electricity input (6000 kWh/tCO2) and the electrochemical stack design
Transportation	2.5 to 38 tCO2 (ideal vs. probable case)	(10 kg/tCO2 to 152 kg/tCO2) × 250 tCO2
Sequestration	Unknown for now	We will improve this through a research based

		peer-reviewed LCA that we are planning to perform in 2023 (collaboration with TU Delft university)
End of life disposal	Unknown for now	We will improve this through a research based peer-reviewed LCA that we are planning to perform in 2023 (collaboration with TU Delft university)

4. Measurement, Reporting, and Verification (MRV)

Section 3 above captures a project's lifecycle emissions, which is one of a number of MRV considerations. In this section, we are looking for additional details on your MRV approach, with a particular focus on the ongoing quantification of carbon removal outcomes and associated uncertainties.

a. Describe your ongoing approach to quantifying the CDR of your project, including methodology, what data is measured vs modeled, monitoring frequency, and key assumptions. If you plan to use an existing protocol, please link to it. Please see Charm's bio-oil sequestration protocol for reference, though note we do not expect proposals to have a protocol at this depth at the prepurchase stage.

> We can directly measure and monitor the extracted (inorganic) carbon from the ocean (e.g., using a TOC analyser machine or a dissolved CO2 sensor or through titration with HCl [4]). The extracted carbon from the ocean, results in 1:1 extraction from the air, based on literature. In practice, if one assumes that the decarbonised water is returned to the surface mixed layer of the ocean (25 m–100 m deep), the time scale for reabsorption of CO2 from the atmosphere is estimated to be within one year [6].
>
> Our simulations (simple Matlab so far) also fits very well with our measurements. We also measure and monitor the flow/ concentration of the extracted gaseous CO2(g) using a GC machine. There are many well established protocols to measure the carbon/ionic concentration of the seawater, see <https://www.iaea.org/sites/default/files/18/07/oa-dickson-chemistry-1901015.pdf> and <https://cdiac.ess-dive.lbl.gov/ftp/oceans/Handbook_2007/Guide_all_in_one.pdf> as examples.
>
> We measure and monitor temperature, pH, applied current density, pressure difference, cell voltage and ionic composition of the sea in line. We will partner up with NIOZ Royal Netherlands Institute for Sea Research to measure the long term effect of our method on marine life. Our collaboration with TU delft and Wetsus <https://www.wetsus.nl/> ensures accurate validated measurements.
>
> [6] Roy-Barman, M., 2016. Marine Geochemistry: Ocean Circulation, Carbon Cycle and Climate Change, 1st edition. Oxford University Press, New York, NY.

b. How will you quantify the durability of the carbon sequestered by your project discussed in 2(b)? If direct measurement is difficult or impossible, how will you rely on models or assumptions, and how will you validate those assumptions? *(E.g. monitoring of injection sites, tracking biomass state and location, estimating decay rates, etc.)*

We will partner up with a third party for underground CO2 storage. In addition to modeling, we will also do monitoring of injection sites in collaboration. As we are connected to the university and knowledge institutes, we will be reading and researching the latest updates on underground CO2 storage.

c. This tool diagrams components that we anticipate should be measured or modeled to quantify CDR and durability outcomes, along with high-level characterizations of the uncertainty type and magnitude for each element. We are asking the net CDR volume to be discounted in order to account for uncertainty and reflect the actual net CDR as accurately as possible. Please complete the table below. Some notes:

- In the first column, list the quantification components from the Quantification Tool relevant to your project (e.g., risk of secondary mineral formation for enhanced weathering, uncertainty in the mass of kelp grown, variability in air-sea gas exchange efficiency for ocean alkalinity enhancement, etc.).
- In the second column, please discuss the magnitude of this uncertainty related to your project and what percentage of the net CDR should be discounted to appropriately reflect these uncertainties. Your estimates should be based on field measurements, modeling, or scientific literature. The magnitude for some of these factors relies on your operational choices (i.e., methodology, deployment site), while others stem from broader field questions, and in some cases, may not be well constrained. We are not looking for precise figures at this stage, but rather to understand how your project is thinking about these questions.
- See this post for details on Frontier's MRV approach and a sample uncertainty discount calculation and this Supplier Measurement & Verification Q&A document for additional guidance.

Quantification component Include each component from the Quantification Tool relevant to your project	**Discuss the uncertainty impact related to your project** Estimate the impact of this component as a percentage of net CDR. Include assumptions and scientific references if possible.
storage	Neglectable < 1 % as the mass of CO_2 injected for geologic storage can be measured directly. It can also be checked for consistency against operational data from the CO_2 capture system.
storage leakage	Low 1-5 % as for terrestrial geologic storage, leakage can be directly monitored during and after the injection period,
Materials	Low 1-5 % as The embodied emissions of any materials consumed during operation, like mineral feedstocks or chemical solvents, can be estimated based on a cradle-to-grave life cycle assessment (LCA) of the material input. We have done this for the membranes, electrodes, tubes/pipes and most of our equipments within our initial LCA
Energy	Low 1-5 % as The emissions associated with energy use for the process can be calculated easily based on the type of electricity used. In our LCA, we have assumed offshore wind based renewable electricity. Our method makes sense if it uses green electricity.

Storage monitoring and maintenance	Low to medium < 15 % We do not have a concrete answer for this but like to do a conservative estimation rather that the best case scenario so we choose medium risks, but based on our current talks with potential storage companies, they all avoid supercritical CO2 and mainly are keen towards empty salt and oil reservoirs which reduce the leakage chance significantly

d. Based on your responses to 4(c), what percentage of the net CDR do you think should be discounted for each of these factors above and in aggregate to appropriately reflect these uncertainties?

10 %
Our approach is very similar to DAC with the benefit that no chemicals/ high temperatures are required. We do benefit from the rich literature on the DAC reducing our and your risks.

e. Will this project help advance quantification approaches or reduce uncertainty for this CDR pathway? If yes, describe what new tools, models or approaches you are developing, what new data will be generated, etc.?

This project will reduce uncertainty for this CDR; ocean capture will become even bigger than DAC, because the concentration of the carbon in the ocean is 140 times more than air, and because the geological footprint of the oceanic capture is 100 times lower than DAC. Costwise, oceanic carbon capture can be cheaper or more expensive than DAC depending on the plant location/ design [7].
Our approach is very similar to DAC. So we benefit from the rich literature on the DAC. Our main difference is that we only need electricity and membranes. We will not require any absorbent/ adsorbent/ chemicals nor any temperature swing modes. Only renewable electricity. This fits very well with the climate goal as it promotes use of renewables.
However, there is not even one commercialized oceanic carbon capture present yet. We want to change that. The data we are looking for are the energy consumption, fouling potential, and MRV of the marine ecosystem as well as the efficiency of the atmosphere-air CO2 transfer.

[7] Eisaman, Matthew D. "Negative emissions technologies: the tradeoffs of air-capture economics." Joule 4.3 (2020): 516-520.

f. Describe your intended plan and partners for verifying delivery and registering credits, if known. If a protocol doesn't yet exist for your technology, who will develop it? Will there be a third party auditor to verify delivery against that protocol or the protocol discussed in 4(a)?

No protocol exists yet. We will develop it together with knowledge institutes. We think of TU Delft university and Wageningen university in the netherlands as well as NIOZ Royal Netherlands Institute for Sea Research. We will also pay/ partner up external (maybe even US based) companies for audits and certifications. Based on our research, the ocean MRV is blooming, so we expect to have enough options in 3-5 years. We are already discussing possibilities with suitable parties.

5. Cost

We are open to purchasing high-cost CDR today with the expectation the cost per tonne will rapidly decline over time. The questions below are meant to capture some of the key numbers and assumptions that you are entering into the separate techno-economic analysis (TEA) spreadsheet (see step 4 in Applicant Instructions). There are no right or wrong answers, but we would prefer high and conservative estimates to low and optimistic. If we select you for purchase, we'll work with you to understand your milestones and their verification in more depth.

a. What is the levelized price per net metric tonne of CO_2 removed for the project you're proposing Frontier purchase from? 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), but we will be using the data in that spreadsheet to consider your offer. Please specify whether the price per tonne below includes the uncertainty discount in the net removal volume proposed in response to question 4(d).

3000 \$/tonne CO_2 (incl. uncertainty discount)

b. Please break out the components of this levelized price per metric tonne.

Component	**Levelized price of net CDR for this project (\$/tonne)**
Capex	450
Opex (excluding measurement)	2200
Quantification of net removal (field measurements, modeling, etc.)[2]	200
Third party verification and registry fees (if applicable)	150
Total	3000 (open to negotiations as this is mainly dependent on the price of electricity)

c. Describe the parameters that have the greatest sensitivity to cost (e.g., manufacturing efficiencies, material cost, material lifetime, etc.). For each parameter you identify, tell us what the current value is, and what value you are assuming for your NOAK commercial-scale TEA. If this includes parameters you already identified in 1(c), please repeat them here (if applicable). Broadly, what would need to be true for your approach to achieve a cost of \$100/tonne?

Parameter with high impact on cost	**Current value (units)**	**Value assumed in NOAK TEA (units)**	**Why is it feasible to reach the NOAK value?**
Stack and membrane costs	120000 \$ for 250 tCO2/yr	25000 \$ for 250 tCO2/yr capacity	The membrane lifetime is increasing while the price decreases (even now by

[2] This and the following line item is not included in the TEA spreadsheet because we want to consider MRV and registry costs separately from traditional capex and opex.

	capacity	(thus 100000 $ for 1 $KtCO_2$/yr unit)	a large order amount). We have assumed a price reduction of ca. 5 times for the stack incl. membranes
(green) electricity	50 cents per kWh for 250 tCO_2/yr capacity	5 cents per kWh	As the capacity of green energy increases, we expect the prices of electricity to decrease. We have estimated 10 times decrease for the $MtCO_2$/yr capacity (7 yrs time span)
To achieve 100$/t, the price and availability of electricity should reduce (>5 times of the current value). Also, the pumpin+electrochemical energy consumption should decrease (up to twice of the current value). Furthermore, the price of membranes and CO_2 storage should be reduced. We expect to have $GtCO_2$/yr capacity with price <100 $/$tCO_2$.			

d. What aspects of your cost analysis are you least confident in?

The amount/ price of electricity, transportation, and MRV (also after sequestration)

e. How do the CDR costs calculated in the TEA spreadsheet compare with your own models? If there are large differences, please describe why that might be (e.g., you're assuming different learning rates, different multipliers to get from Bare Erected Cost to Total Overnight Cost, favorable contract terms, etc.).

We have used the X-prize calculation model previously. These prices are comparable. With our own model.

f. What is one thing that doesn't exist today that would make it easier for you to commercialize your technology? (e.g., improved sensing technologies, increased access to X, etc.)

Unlimited renewable electricity with costs of 5 cent/ kWh

6. Public Engagement

In alignment with Frontier's Safety & Legality criteria, Frontier requires projects to consider and address potential social, political, and ecosystem risks associated with their deployments. Projects with effective public engagement tend to:

- Identify key stakeholders in the area they'll be deploying
- Have mechanisms in place to engage and gather opinions from those stakeholders, take those opinions seriously, and develop active partnerships, iterating the project as necessary

The following questions help us gain an understanding of your public engagement strategy and how your project is working to follow best practices for responsible CDR project development. We recognize that, for early projects, this work may be quite nascent, but we are looking to understand your early approach.

a. Who have you identified as relevant external stakeholders, where are they located, and what process did you use to identify them? Please include discussion of the communities potentially engaging in or impacted by your project's deployment.

> Key stakeholders are local governments and people who are living near our Pilot and future plants. For our pilot plant we are already in talks with the Dutch Province "Friesland". We will partner with them not only on the possible positive output of our work (deacified waters, enhanced biodiversity) but also to mitigate the possible risks. We are also consulting them in regards to energy and storage facilities. We are building a tight relationship with the local governments and this is exactly the way we will proceed in the near future in relation to other plant locations. Upon today, the local government is positive about our project, which can be seen from the fact that they funded us with a (small) public grant.
>
> The capital of the Province Friesland, Leeuwarden, is already a strong place for applications, innovations and research in the water sector. It is known worldwide that a great deal of expertise in the water sector has been gathered in Leeuwarden. With our company SeaO2 in Leeuwarden we can benefit from this rich network. Moreover, we can supplement existing knowledge and be among the pioneers in the field of CO2 capture.
>
> We will take the power of local communities into account. In Groningen, the province next to Friesland, much has been done about earthquakes caused by natural gas extraction. We might Store CO2 in these empty gas reservoirs in The Wadden Sea and The North Sea. This probably raises questions like the expected future stability of these fields etc. We will work together with scientific advisors like TNO (applied science research) and EBN B.V. Energy Management Netherlands on topics like these to get the support from our local stakeholders.

b. If applicable, how have you engaged with these stakeholders and communities? Has this work been performed in-house, with external consultants, or with independent advisors? If you do have any reports on public engagement that your team has prepared, please provide. *See Project Vesta's community engagement and governance approach as an example and Arnestein's Ladder of Citizen Participation for a framework on community input.*

> See 6a. We think this important matter should be handled internally. when we scale up we will certainly hire local agencies, but always under the supervision of a SeaO2 team member

c. If applicable, what have you learned from these engagements? What modifications have you already made to your project based on this feedback, if any?

> N/A

d. Going forward, do you have changes to your processes for (a) and (b) planned that you have not yet implemented? How do you envision your public engagement strategy at the megaton or gigaton scale?

When scaling up we will encounter different national and local authorities, not only in The Netherlands. We will adjust the process and way of working over time taking into account the local situation (City/Province/Country X).

7. Environmental Justice[3]

As a part of Frontier's Safety & Legality criteria, Frontier seeks projects that proactively integrate environmental and social justice considerations into their deployment strategy and decision-making on an ongoing basis.

a. What are the potential environmental justice considerations, if any, that you have identified associated with your project? Who are the key stakeholders? Consider supply chain impacts, worker compensation and safety, plant siting, distribution of impacts, restorative justice/activities, job creation in marginalized communities, etc.

Our current lab facility is based in Leeuwarden (Netherlands), the European capital of water technology. Our prototype will probably be based closeby in the same Province, Friesland.

There are several empty underground (gas and oil) fields available in the Northern Netherlands that enable $CO_2(g)$ storage for the CCS route, which makes it possible to directly reduce the greenhouse gas concentration in the region.

At first we will work on our CCS business model, but we envision a big CCU market for green CO_2 as well. The Northern part of the Netherlands is strong in the field of agriculture; our extracted green $CO_2(g)$ can be used directly in greenhouses to enlarge the crop and as fertilizer. Such a development benefits both the water sector and the agricultural sector, while drastically reducing the ecological footprint of (local) agriculture.

We will source our materials and human resources locally as much as possible, which will have the least possible impact on the environment and as much as possible on the local economy.

b. How do you intend to address any identified environmental justice concerns and / or take advantage of opportunities for positive impact?

The (partly) unknown risks on the ocean ecosystem is an important matter to us. First, a small-scale thorough study needs to be applied to measure and more importantly monitor the effect of the dissolved carbon/ bicarbonate removal from the ocean. (Unwanted) precipitation of $CaCO_3$ reduces alkalinity if the ocean water is mixed with the acid stream, and thus needs to be avoided (or only applied in combination with possible reverse osmosis plants). We have (and remain having) close partnership with knowledge institutes and multidisciplinary scientists to be able to predict the unknown scenarios and by the help of our advisory team, tackle them on time.

[3] For helpful content regarding environmental justice and CDR, please see these resources: C180 and XPRIZE's Environmental Justice Reading Materials, AirMiners Environmental and Social Justice Resource Repository, and the Foundation for Climate Restoration's Resource Database

8. Legal and Regulatory Compliance

a. What legal opinions, if any, have you received regarding deployment of your solution?

N/A

b. What permits or other forms of formal permission do you require, if any, to engage in the research or deployment of your project? What else might be required in the future as you scale? Please clearly differentiate between what you have already obtained, what you are currently in the process of obtaining, and what you know you'll need to obtain in the future but have not yet begun the process to do so.

In the process of obtaining permits in The Netherlands:

- Permits to use the seawater locally as an input in our plant/prototype
- Permits for the return of deacidified ocean water (output)

Our storage partners:

- Our storage partners need permits to geological storage of carbon dioxide (partners)

When we plan to set up a factory in another country, we will first research what permits are needed. We will follow the same process as now in the Netherlands

c. Is your solution potentially subject to regulation under any international legal regimes? If yes, please specify. Have you engaged with these regimes to date?

We still have to assess this in greater detail. As the Netherlands is our pilot country we expect that the regulations around using seawater, extracting CO2 and returning the deacidified stream to the ocean will be somewhat similar. Our solution reduces the greenhouse effect and potentially enhances biodiversity (it battles ocean acidification and only removes the inorganic carbon while leaving the other ions/ components in the seawater unchanged). We therefore do not expect much opposition from regulation now that climate change is an important topic on more and more agendas. We will engage (and assess) with the (local) authorities when our country strategy is in place.

d. In what areas are you uncertain about the legal or regulatory frameworks you'll need to comply with? This could include anything from local governance to international treaties. For some types of projects, we recognize that clear regulatory guidance may not yet exist.

For now, we focus on the Netherlands (as explained in 8c). We will educate ourselves for any future international possibilities as we develop.

e. Do you intend to receive any tax credits during the proposed delivery window for Frontier's purchase? If so, please explain how you will avoid double counting.

Not at the moment.

After the pilot phase we would like to acquire tax credits from the Dutch tax authorities and plan to do the same when upscaling to other countries as well. Possible opportunity in the Netherlands is SDE++ (https://www.rvo.nl/subsidies-financiering/sde). We expect this to refer to the period after this pilot project. We can easily measure and monitor the amount of extracted carbon from the ocean. We will keep records on the purchases and credits vs. the amount of carbon captured to avoid any double counting.

9. Offer to Frontier

This table constitutes your **offer to Frontier**, and will form the basis of contract discussions if you are selected for purchase.

Proposed CDR over the project lifetime (tonnes) *(should be net volume after taking into account the uncertainty discount proposed in 4(c))*	initial 222 tCO2 (with the increased possibility as explained in table 1-h)
Delivery window *(at what point should Frontier consider your contract complete? Should match 1(f))*	Q4-2024
Levelized Price ($/metric tonne CO_2) *(This is the price per tonne of your offer to us for the tonnage described above)*	3000 $/tCO2 (open to negotiation)

Application Supplement: Ocean

(Only fill out this supplement if it applies to you)

Physical Footprint

1. Describe the geography of your deployment, its relationship to coastlines, shipping channels, other human or animal activity, etc.

> We capture carbon directly from the ocean. This can be done from any ocean/ seawater (or even river water). Our discussions with experts at NIOZ (Royal Netherlands Institute for Sea Research) inform us that, considering the carbon cycle and ocean-atmosphere equilibrium, the best locations are those close to the equator. However, for the 250tCO2/yr and 1 ktCO2/yr plants, we are going to use the north sea (from the Netherlands) and have the capture plant next to the sea.
> For the MtCO2/yr plant(s) we aim to mount our stack above old oil/gas offshore rigs to eliminate CO2 transportation and just inject the captured CO2 directly underground.
> It is also possible to mount the capture plant with reverse osmosis desalination pants or mounted on a ship but especially the latter is the 10 year planning for us.

2. Please describe your physical footprint in detail. Consider surface area, depth, expected interaction with ocean currents and upwelling/downwelling processes, etc.

    a. If you've also filled out the Biomass supplement and fully articulated these details there, simply write N/A.

> We will work with the surface layer of the ocean (i.e., the upper 100 m) and apply a sand filter for water pretreatment prior to the carbon capture. upwelling/downwelling processes should not have an effect on the carbon capture as the concentration of the dissolved inorganic carbon is even higher in depth. They might have an effect on the re-equilibration after carbon capture though. We also do not expect challenges with interaction with ocean currents at the moment. However, we are aware that as we go further, we will need more detailed information on these matters.
>
> To put this in perspective, extracting 1 GTon-CO2 per year (~ 2.7 % of the total global CO2 emission) from the ocean surface layer (i.e., the upper 100 m) requires processing only a fraction of 0.00025 of this layer's volume. From every 1 L of seawater, approximately 47 mL CO2 (g) and/ or 208 g CaCO3 (s) can be extracted. When the dissolved inorganic carbon (DIC) content is extracted from the ocean, the decarbonized stream can be directed back to the ocean where it can re-equilibrate with the atmosphere again through absorbing CO2(g) from the atmosphere

3. Imagine, hypothetically, that you've scaled up and are sequestering 100Mt of CO_2/yr. Please project your footprint at that scale, considering the same attributes you did above (we recognize this has significant uncertainty, feel free to provide ranges and a brief description).

    a. If you've also filled out the Biomass supplement and fully articulated these details there, simply write N/A.

Our geographic footprint for the carbon capture step will not increase linearly with capture capacity. To go from 1KtCO_2/yr (using one electrochemical stack) scale to 1 MtCO_2/yr cpture capacity, we need to have 1000 stacks. Each stack will have dimentions of 1.5m*1.5m*0.15 m (thus 0.34 m3), thus a 1000 stacks will require 334 m3 which can fit within a house. However, the main footprint is that of the volume of the seawater that is needed for carbon capture.

For 1 MtCO_2/yr capture plant, we will need at least 40 million m3/day water (for the process as shown in Figure 2A). To put this in perspective, the largest desalination plants in the world (Ras Al Khair, SaudiArabia) desalinates 1 million m3/d of water. Thankfully, the main difference between our oceanic carbon capture and desalination units is the waste/ brine management: our prices will not change anything in the ocean water except extracting CO_2 from it. The treated seawater can thus return safely to the ocean with no waste or chemicals needed.

After capture, we need to store the captured-CO_2 underground (via 3rd-parties) and we must improve our footprint estimation accordingly.

Potential to Scale

4. Building large systems on or in the ocean is hard. What are your core engineering challenges and constraints (not covered already within 1(n)? Is there any historical precedent for the work you propose?

We want to place our capture stack on top of old/used oil/gas offshore platforms; to enable capture and storage (injection in empty underground oil/gas reservoirs) in one go. Even Though challenging, many offshore projects were done in the past safely, e.g., oil/gas production, shipping and wind turbine installation/ production.

The capture unit will be designed in such a way that it can be operated on shore from distance, reducing the risks and complexity. The building of the unit and mounting will be done via 3rd parties and we don't have the expertise in house. The advantage is that because of the climate goals, the oil/ gas production must decrease; meaning that lots of old offshore units will become available. Furthemore, turning an old oil/gas production rig to carbon capture saves lots of costs/ materials and has a great business model advantage both for us and the previous owner of the platform.

Externalities and Ecosystem Impacts

5. What are potential negative impacts of your approach on ocean ecosystems?

The sand filter and pumping can distort ocean life including fish, birds etc. However, we don't yet know the extent of this distortion and we are going to investigate that. Furthermore, as we do not change the seawater pH drastically, and even can make it more alkaline (to restore reef, and shells), we don’t expect a negative impact there.

Still, the unknown risks on the ocean ecosystem because of decarbonisation are probably the most important category. We plan to partner with 3rd parties such as NWO-NIOZ Royal Netherlands Institute for Sea Research already this year to study, measure and more importantly monitor the effect of pH-swing based ocean decarbonisation.

6. How will you mitigate the potential for negative ecosystem impacts (e.g., eutrophication and alkalinity/pH)? How will you quantify and monitor the impact of your solution on ocean ecosystems and organisms?

We will quantify and monitor the impact of your solution on ocean ecosystems and organisms by partnering with 3rd parties specialized on this topic. We expect no eutrophication as we do not add/ remove anything from the ocean except the inorganic carbon (i.e., bicarbonate ions).as for alkalinity, we can control our process to increase alkalinity but it is not a necessity for the process. We can easily measure, monitor and control the pH.