CarbonBlue

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

CarbonBlue Ltd.

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

Israel

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

Dan Deviri

Brief company or organization description <20 words

CarbonBlue develops a safe, scalable, and profitable Direct Ocean Removal technology for climate change mitigation.

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

[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.

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.

The ocean holds about 98% of the CO2 in the carbon cycle, making it the largest CO2 reservoir in the world. CarbonBlue, using Direct Ocean Removal (DOR) of CO2, makes room for more atmospheric CO2 to be absorbed by the ocean while preserving the mineral composition of the seawater. Since CO2 in the ocean is 140 more concentrated than in the atmosphere, CarbonBlue's facilities are compact, and the CAPEX required is small relative to those of direct air capture technologies. This ability leverages the benefits the ocean has to offer for cost-efficient Carbon Dioxide Removal (CDR) with minimal uncertainty regarding adverse environmental impacts.

CarbonBlue's DOR process extracts CO2 from the ocean, thereby reducing the pCO2 in the seawater. The extracted CO2 is durably sequestered for more than 1000 years using existing technologies, such as surface mineralization or geosequestration. In equilibrium, the pCO2 of the top ocean layer is equal to the partial pressure of atmospheric CO2. Thus, the reduction the seawater's pCO2 makes it sub-saturated and causes it to reabsorb a similar amount of atmospheric CO2 from the atmosphere by natural processes of ocean-atmosphere gas exchange, leading to reduction of atmospheric CO2 levels and thus qualifying to carbon credits. Figure 1 below shows the results of a simplistic simulation that illustrates the capability of the ocean to absorb carbon from the atmosphere following oceanic carbon removal.

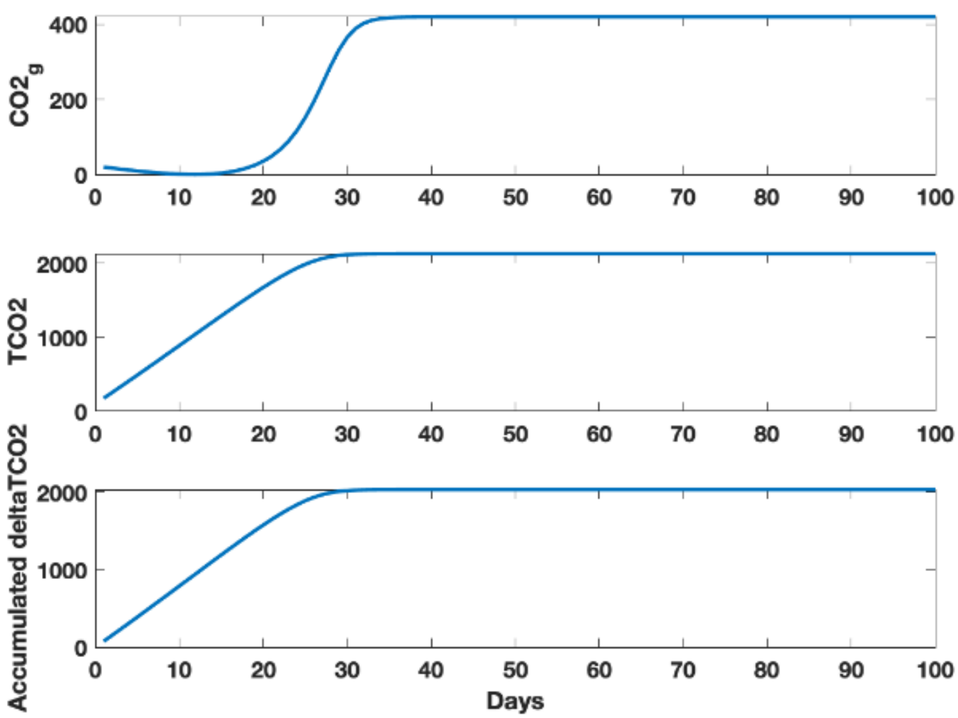

Figure 1: 1D simplified model illustrating the magnitude and rate of the ocean's response to the complete removal of CO2 from its water while conserving its alkalinity. Time evolution of pCO_2 (ppm), Total CO_2 (micromolar/kg), and the amount of carbon (in micromoles) absorbed by the ocean, for ALK=2300 micromolar/kg, S=33 psu, Piston velocity (a proxy for DOR rate) $5e^{-5}$ m/s, and T=30 °C.

The technology that CarbonBlue is developing is based on chemical looping, where minerals that are naturally abundant in seawater are used to shuttle the CO2 dissolved in seawater to a concentrated gas phase. The chemical carriers of CO2 are transiently produced and consumed within the reactors. Figure 2 presents a schematic flow diagram of our chemical looping process.

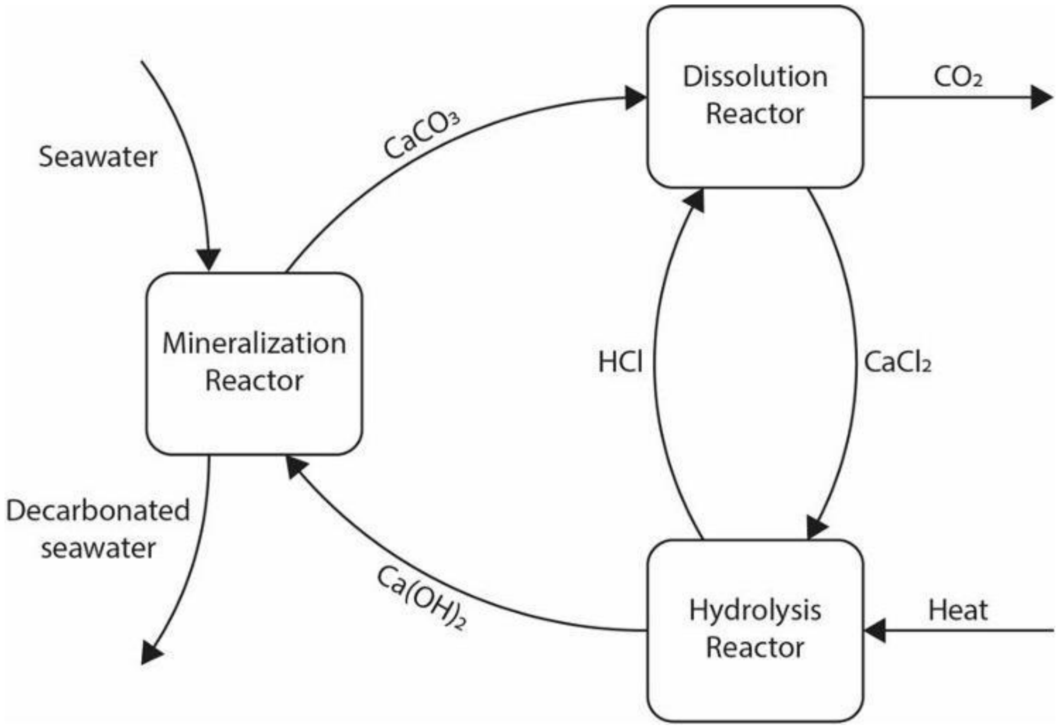

Figure 2: Schematic description of CarbonBlue’s process

Our approach to DOR is qualitatively distinct from most existing techniques, which are electrochemical, namely facilitating DOR using electric fields and currents generated by electrodes to force ions through membranes in processes that are otherwise not thermodynamically spontaneous. Because of this distinction, our process presents two significant advantages that make our system the best in class:

1. It can be executed with cheap and robust chemical reactors, membrane and electrode-free, significantly reducing system complexity, capital, and operative expenses compared to the existing approaches.

2. It can remove CO2 from low-salinity waters, such as inland freshwater bodies.

Existing DOR approaches require salinity for the conductance of electrical currents and are unable to remove CO2 effectively from low-salinity waters. Inland waters act as a net source of atmospheric CO2 of a magnitude of 7.7 gigatons-CO2/year [Raymond et al., Nature 2013]. Moreover, inland waters such as rivers and lakes represent closed or semi-closed systems in which, in contrast to seawater, direct measurement of atmospheric CO2 reabsorption following DOR is possible, as the decarbonated water does not dilute into an open system (as it would in seawater). Therefore, in addition to the ability to extract CO2 from seawater, our novel technology can lead to a new type of CDR, direct inland water removal that does not currently exist, tackle a significant natural source of CO2, and offer a simplified MRV challenge compared to DOR. We now describe CarbonBlue's process in detail.

When dissolved in water, CO2 forms a solution of bicarbonate (HCO3-) and carbonate (CO3-2) ions, whose relative ratio of concentrations is determined by the pH of the water. Most of these ions are bicarbonate when seawater is at its natural pH (~8.1-8.2).

CarbonBlue's process uses three chemical reactions to replace these carbonate and bicarbonate ions with hydroxide ions, releasing gaseous CO2 via the chemical reaction:

$$HCO^-_{3(aq)} \rightarrow OH^-_{(aq)} + CO_{2(g)} \quad (1)$$

Then, the decarbonated and hydroxide-rich water is returned to the ocean, where the reverse of reaction (1) takes place, reabsorbing atmospheric CO2.

In the first reaction, our proprietary mineralization reactor mixes lime (Ca(OH)2) with seawater. The lime dissolves in the seawater, locally increasing its pH and converting bicarbonate to carbonate ions. The increased concentration of carbonate ions promotes precipitation of solid calcium carbonate (CaCO3). The following reaction describes the conversion of bicarbonates to carbonate ions and their precipitation:

$$HCO^-_{3(aq)} + Ca(OH)_{2(aq)} \rightarrow CaCO_{3(s)} + OH^-_{(aq)} + H_2O_{(l)} \quad (2)$$

Furthermore, to enhance the mineralization rate, the seawater/lime mixture is used to fluidize small grains of CaCO3. The fluidized grains of CaCO3 provide a large surface area for the mineralization reaction, which shortens the mineralization time from roughly a day (in conventional precipitation tanks) to a couple of minutes in our proprietary reactor design.

In the second reaction, which takes place in the dissolution reaction, the CaCO3 solids are dissolved in a dilute solution of hydrochloric acid via the chemical reaction:

$$CaCO_{3(s)} + 2HCl_{(aq)} \rightarrow CO_{2(g)} + H_2O_{(l)} + CaCl_{2(aq)} \quad (3)$$

This reaction consumes acid and releases the CO2 previously dissolved in the seawater as a pure gas. Then, the third reaction, which is endothermic and takes place in our proprietary hydrolysis reactor, requiring a temperature of 500 degrees Celsius, regenerates both the acid consumed in reaction (3) and the calcium hydroxide consumed in reaction (2). The following chemical formula describes the hydrolysis reaction:

$$CaCl_{2(aq)} + 2H_2O_{(g)} + Heat \rightarrow Ca(OH)_{2(s)} + 2HCl_{(g)} \quad (4)$$

Summation of reactions (2-4) yields reaction (1), indicating that the combination of these three reactions has a net CDR result.

When compared with alternative DOR approaches, our technology offers multiple advantages:

1. Our primary energy source is heat, which is much cheaper than electricity.
2. The energy consumption of the process, 1.1 MWh/ton-CO2, is low.
3. Our low working temperature allows the integration of renewable and waste heat.

The DOR approach described here entails multiple novel aspects which have the potential to impact non-ocean-based CDR and the decarbonization of multiple industries, which are part of the priority innovation areas identified in the RFP.

First, the combination of reactions (3) and (4) above results in an approach for the production of metal hydroxides that can replace traditional calcination and slaking in various industries, such as cement, pulp & paper, and even in DAC processes (e.g., Carbon Engineering and Heirloom). As shown in Fig. 3, this presents innovation in a low-energy synthesis of bases (priority innovation area) since it does not include a highly exothermic reaction such as slaking, which releases low-grade heat that cannot be used in the process, so that the energy input for the production of the base can be reduced by about 30% compared to traditional processes.

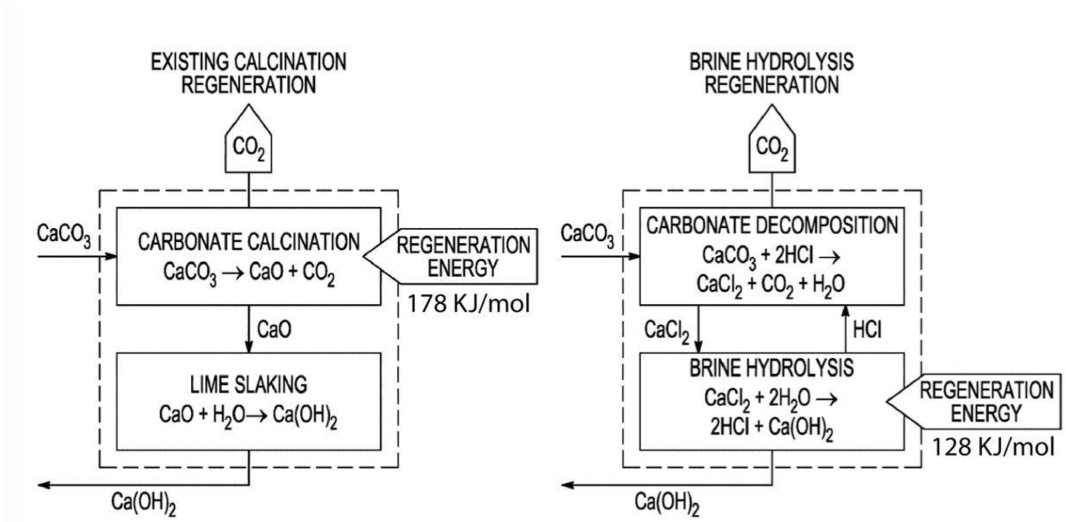

Figure 3: Energy consumption of our lime regeneration process compared to traditional calcination and slaking; adapted from [US Patent US20220288556A1].

Furthermore, the reduced working temperature of the lime production process is significant for another priority innovation area, the integration of CDR into existing industries. The operating temperature of our hydrolysis reactor, 500 degrees Celsius, is within the temperature range of waste heat in various sectors such as power generation, mining, iron & steel, and ammonia, which utilize water cooling. In these industries, the waste heat can power CO2 removal from the cooling water stream. Then, the removed CO2 can be sequestered into the waste streams of these industries. In addition, the lower working temperature allows for integrating our DOR process with renewable heat sources, such as solar and biomass, that cannot support traditional calcination due to its high-temperature requirement. This provides an important industrial use case for the renewable energy industry for the utilization of renewable heat without converting it to electricity which leads to a loss of roughly two-thirds of the energy content.

Lastly, as mentioned above, CO2 removal from low salinity waters, such as inland waters, is an important innovation included in the priority innovation areas. Our new approach for DOR enables CO2 drawdown quantification, which was not possible before. By removing CO2 from inland waters, we can directly measure the absorption of atmospheric CO2 by chemical analysis of the decarbonated water, which does not significantly dilute over time (for example, sampling river water downstream to the point of CO2 removal).

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.

CarbonBlue is developing a CDR technology that can remove gigatons of CO2 from all kinds of surface waters, at a low cost, with a small physical footprint, and in an environmentally safe and measurable way. For its first commercial projects, CarbonBlue intends to leverage existing facilities, such as desalination and water-cooling systems, while saving energy and costs for those facilities.

CarbonBlue is building a 1000-tonCO2/year CDR facility integrated within an operating desalination plant as a first commercial step. Removal of CO2 from seawater before their desalination solves a significant pain point of desalination and reduces costs, which is why CarbonBlue targets desalination plants as early-stage partners. The desalination plant CarbonBlue works with is located along the southern Mediterranean coast of Israel and is one of the world's largest seawater reverse osmosis plants. The facility would demonstrate CarbonBlue's DOR method's cost-effectiveness and ability to reduce desalination production costs.

The 1kton facility will remove the CO2 from a portion of the intake of the desalination plant. Following a successful demonstration of the project, the facility would be scaled up to remove CO2 from the entire desalination plant intake, enabling a capacity of up to 30,000 tons-CO2/year. The co-benefits for the desalination plant can save up to 10% of its operational costs.

The desalination plant is located near a wastewater treatment facility, which discharges water to the ocean with a high concentration of dissolved organic and inorganic CO2. As a result, the vicinity of the discharge region acts as a CO2 source, releasing CO2 into the atmosphere. CarbonBlue's decarbonated seawater will reduce the CO2 emissions from the ocean to the atmosphere.

Like many other desalination plants, the desalination plant that CarbonBlue works with consumes CO2 as part of its posttreatment processes. A portion of the removed CO2 would feed the posttreatment process, thus reducing costs and avoiding emissions of their supply chain. The excess CO2 will be mineralized and permanently stored. CarbonBlue is in discussions with several CO2 mineralization companies regarding the proposed project that will utilize the removed CO2 and work with local cement manufacturing and or processing companies.

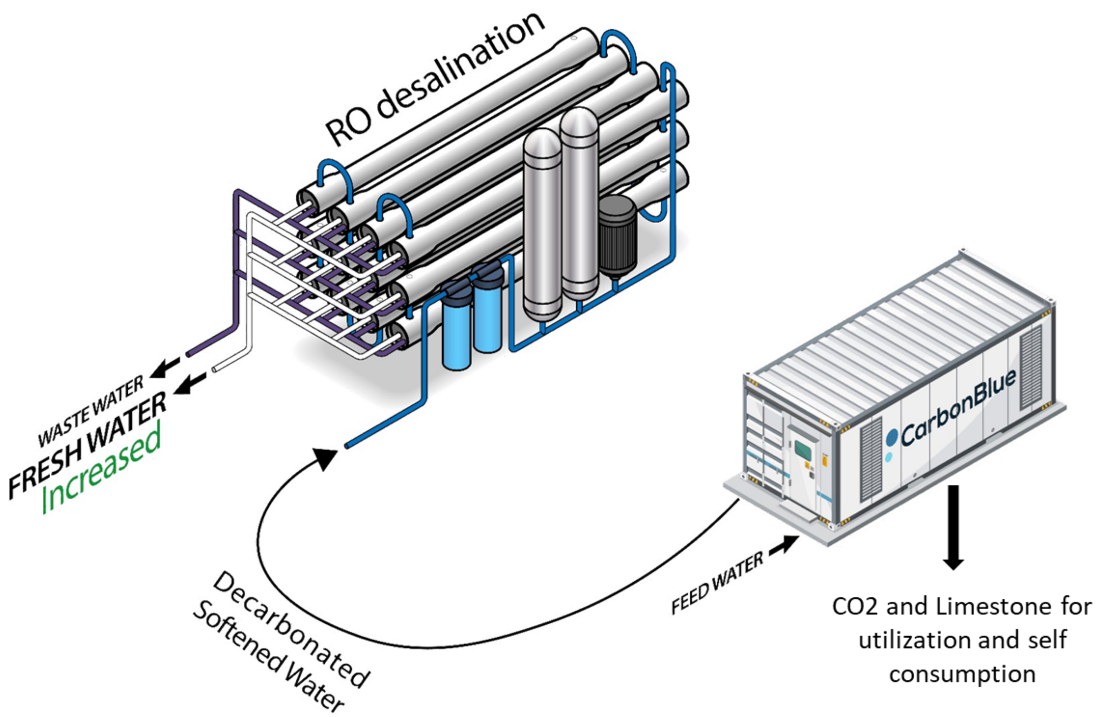

Figure 4: Schematic cartoon of a DOR module integrated with a reverse osmosis desalination plant

CarbonBlue's process doesn't require high salinity or ultrafiltration. Therefore, the technology CarbonBlue is developing can be integrated with many existing facilities in addition to desalination plants. A successful demonstration pilot on desalination intake would validate the technology for any water system, including systems with much larger water flow and CO2 capacity than desalination. Such facilities include seawater cooling systems for power plants, smelters, and ammonia production. Typically, water-cooling systems of industrial facilities can provide water to support DOR at a scale of hundreds of kilotons for each project. We estimate that the total global water flow of cooling systems on its own is sufficient for removing 0.5GtonCO2/year.

After utilizing existing pumping infrastructure, CarbonBlue can leverage abandoned O&G platforms that otherwise would need to be decommissioned. These offshore platforms would eliminate the need to pump large amounts of seawater to the shore and, in some cases, provide existing infrastructure for accessible subsurface storage in the depleted O&G reservoir (when the depleted reservoir meets the requirements for a geosequestration site), reducing the need for costly CO2 transportation. Due to the compactness of CarbonBlue's facilities, some abandoned offshore platforms can support the removal of more than 1MtonCO2/year each. In the Gulf of Mexico alone, there are more than 3000 abandoned offshore platforms, potentially enabling more than 1GtonCO2/year CDR based on our technology. Of course, CarbonBlue can also develop and construct standalone DOR facilities independent of any existing infrastructure.

CarbonBlue's technology is not based on electrochemistry and, therefore, not affected by water salinity, so that it can remove CO2 from inland water sources such as rivers, reservoirs, and great lakes. The pCO2 (partial pressure of CO2, whose gradient across the air-sea interface defines the direction of carbon flux) of many of the inland water sources is larger than that of the atmosphere so that they release CO2 into the atmosphere. The total amount of CO2 that is released is estimated to be 7.7 gigaton-CO2/year [Raymond et al., Nature 2013], thus representing a unique and potentially groundbreaking use case for CarbonBlue's technology that supports greater scalability. Notably, although the operating parameters of the reactors could vary among different water sources, the reactors themselves are the same.

An important advantage of removing CO_2 from freshwater sources, such as rivers, reservoirs, and lakes, is the simplicity of quantifying the carbon removed. CarbonBlue develops a "Double Lock" MRV mechanism where the removed CO_2 is measured twice. The first time, the CO_2 is measured at the output stream of the process, which represents the total amount of CO_2 removed from the water reservoir. The second measurement is tracking the pCO_2 gradient between the water and air at the different locations (e.g., downstream a river) and times and comparing it to a baseline measured without the CO_2 removal facility to quantify the changes in CO_2 fluxes between the atmosphere and the water due to the use of our technology. In the case of rivers, lakes, or reservoirs, this measurement is straightforward since the water bodies are bounded. Combining the two measurements can accurately quantify the amount of carbon removed.

In the case of ocean removal, the system is more complex, and a General Circulation Model (GCM) would be generated to support the quantification process, to be complemented and validated by field measurements. For the 1kton facility, CarbonBlue will use a modification of an existing high-resolution (300 meters) model of the Eastern Mediterranean Sea (see [Solodoch et al., Journal of Physical Oceanography 2023]), supported by its MRV team and scientific advisors (the team includes academic experts in physical oceanography and GCM modeling, biogeochemistry and marine biology with experimental and observational expertise).

CarbonBlue's CDR cost at the 1kton/year scale is around $400/ton. At that scale, the main contributors to the cost are labor ($80/ton) and CAPEX per unit capacity ($2,000/ton/year). These two components would be significantly reduced with scale. The reactors of the process are based on existing and available components (pipes, pumps, tubes, etc.), and their cost per unit capacity decreases with scale, up to the scale sufficient that enables 100kton CO_2 removal. At that scale, current projections predict that CarbonBlue's cost could go as low as $60/ton, divided half CAPEX and OPEX. This cost could be further reduced by integrating the process with existing infrastructure.

CarbonBlue will collaborate with strategic partners that can benefit from our DOR technology to reach that target. This will allow CarbonBlue to continuously scale up and derisk the technology toward global, large-scale implementation of DOR facilities with local project developers. The funding of Frontier's prepurchase will support the construction of our first-of-a-kind facility, which will pave the way to such joint ventures and technological scale-up.

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.

Although the science of our solution is solid, there are still engineering risks related to the integration and scale-up of our reactors. These include the automatic transfer of mass between the reactors with minimal losses (in chemical looping, such material losses, if too large, necessitate external makeup), energy recovery between the products of the hydrolysis reactor and its inputs, and maintenance of the facility after long, continuous operation. CarbonBlue currently operates a small-scale batch facility where each one of the reactors is tested and optimized. CarbonBlue is also developing an intermediate-scale facility (10 tonsCO_2/year) to test the integration of the reactors and the mass and energy exchange between them. In addition, CarbonBlue consults with RHDHV, an engineering firm that has vast experience in scaling up water technologies (and specifically fluidized bed reactors such as the mineralization reactor).

One of the main operational risks is the time needed to obtain permits for the construction and commissioning of a project. This risk is significantly reduced by utilizing existing seawater pumping and disposal infrastructure, eliminating the need for additional marine infrastructure and permits. CarbonBlue is accompanied by the best-known environmental and regulatory advisors in Israel and is planning the proposed project in such a way as to minimize these risks. For example, designing portable reactors that do not require special permits for construction. Also, the project planning is simpler that way because we can fabricate all the reactors and units in one site and transport them to and assemble them at the location of the facility once the required permits are obtained.

In addition to the “conventional” permitting required by any business or industrial facility, our DOR facility requires a unique permit for water discharge to the ocean. CarbonBlue has conducted meetings with the Israeli Ministry of Environmental Protection in which we presented our proposed project and discussed the current regulations and permitting process. Following that meeting, CarbonBlue commenced research with the Israel Oceanographic and Limnological Research studying the effect of decarbonated effluent water of our DOR process on Lobophora, a brown alga that is a primary producer and a key species of the eastern Mediterranean marine ecosystem. The results of the research show that CO2 removal using our process at the levels that maximize mineralization rate per unit area (which we aim for) is safe for the algae. These positive results will be used as part of the permitting process. Regardless of the permitting process, CarbonBlue will continue to investigate the environmental impact of its process on various biological species and marine ecosystems and will communicate the results publicly and transparently.

One last risk is related to the MRV of the ocean removal process. Although the amount of sequestered seawater CO2 can be directly measured, measurement of atmospheric CO2 reabsorption by the decarbonated seawater is challenging. CarbonBlue consults with the most influential scientific experts and thought leaders regarding ocean MRV and is developing an MRV methodology aligned with the mainstream of this developing discipline. Industry-wide transparency and collaboration are crucial for scientific and social acceptance of this proposed scalable technology.

In the proposed project, CarbonBlue plans to feed the effluent, decarbonated seawater to the desalination plant the project will be co-located with to take advantage of the co-benefits for desalination. In such a case, the stream with low PCO2 levels, which will absorb CO2 from the atmosphere, will be the desalination brine and will be discharged using the brine discharge infrastructure of the plant. This introduces an MRV risk as the brine is denser than water and, as a result, may sink and only partially exchange gases with the atmosphere.

The oceanographic model we are developing specifically deals with this uncertainty. If the results of our study indicate that reduction of atmospheric CO2 levels are hindered due to incomplete gas exchange with the atmosphere, we will take advantage of an adjacent wastewater treatment plant to mitigate this MRV risk. The effluent stream of this wastewater treatment plant is discharged close to the desalination plant brine and is rich in dissolved organic carbon (DOC). This DOC mineralizes over time and increases the pCO2 of the water, leading to degassing of CO2. We will work to combine the low-pCO2 decarbonated stream we produce with the high-pCO2 treated wastewater stream to reduce the amount of CO2 it emits (thus reducing the magnitude of degassing). This suggested approach closely mimics Planetary’s methodology [Burt et al., 2023] that was recently approved by Shopify, a Frontier member, thus greatly reducing MRV uncertainties.

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*	320 tons

uncertainty discount proposed in 5c)	
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	Q3 2024 – Q4 2025
Levelized Price (\$/ton CO_2)* *(This is the price per ton of your offer to us for the tonnage described above)*	1250

** 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).*