Vycarb, Inc.

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

Vycarb, Inc.

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

Brooklyn, New York

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

Garrett Boudinot

Brief company or organization description <20 words

Vycarb is developing an integrated real-time carbon measurement and alkalinity addition system to deliver high-quality CDR in natural waters.

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.

Vycarb is developing a real-time direct quantification approach to deploy fully-measured, ecologically beneficial carbon dioxide removal and storage (CDR) via alkalinity addition in natural waters using a novel sensing apparatus coupled to a batch water processing system. Our sensor array measures dissolved CO_2, HCO_3, and CO_3 in real-time and at lower cost than traditional in-field and in-lab measurement approaches, enabling a robust, reduced cost and improved uncertainty solution for measuring, reporting, and verifying (MRV) a range of water-based CDR. We are currently piloting a small-scale version of our integrated water carbon measurement and removal system in coastal New York, measuring, controlling, and producing CDR by converting dissolved biogenic CO_2 into stable, dissolved inorganic carbon (HCO_3 and CO_3) via the addition of calcium and magnesium. In this project, we will deploy, test, and sequentially scale up to a larger, floating batch-treatment alkalinity addition system for fully measured CDR in naturally high CO_2 waters.

Our goal is to provide low-cost, real-time quantitative MRV for our CDR approach *and* to catalyze other ocean CDR approaches. This project specifically addresses Frontier's 2023 priority innovation area for new approaches to ocean-based CDR to further field knowledge and enable decision-making about responsible deployment by generating years of real-time quantitative verification data for alkalinity addition with a robust measurement approach for high-volume CDR in natural waters. Vycarb will share measurement, ground-truthing, and ecosystem impact results with the ocean CDR community to further enable responsible decision-making broadly.

Vycarb's integrated carbon measurement and removal system (Fig. 1) consists of three main components. A main water containment holds discrete volumes of natural water for measurement and CDR. A sensor apparatus physically controls the discrete volume of water to enable real-time measurement of dissolved CO_2, HCO_3, and CO_3 before, during, and after CDR for full accounting. An alkalinity dissolution chamber mechanically dissolves alkaline minerals in water, generating an alkaline solution to rapidly and efficiently convert CO_2 to HCO_3 and CO_3. After CDR, the main containment releases amended waters into the natural open water system, where the combined alkalinity and correspondingly produced HCO_3 remain stable for >10,000 years (Renforth and Henderson, 2017).

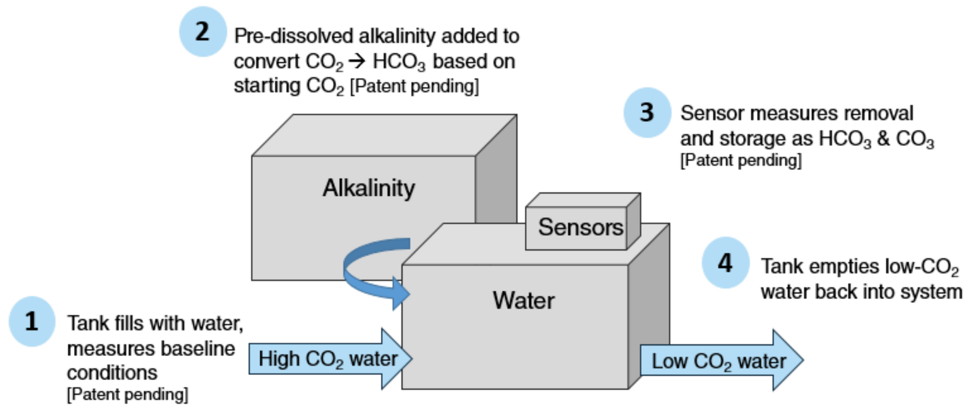

Figure 1: A simplified schematic showing the major components of Vycarb's integrated water-based carbon measurement and removal system, where water enters a discrete containment for rapid measurement (1), pre-dissolved alkalinity is added to the containment based on the baseline conditions (2), continuous measurement is applied to the water containment to trace the CDR reaction (3), and water is released upon achieving stable CDR while maintaining ecologically safe water chemistry (4). Real-time data and system status are remotely transmitted to an online dashboard at each step.

The real-time sensor apparatus measures the baseline conditions, including CO_2, carbonate saturation state, and pH for each batch treatment cycle. This information controls the precision addition of alkalinity, to ensure that carbonate saturation is not reached (avoiding carbonate precipitation and release of CO_2; Moras et al., 2022), and that pH is at or below 8.6 to avoid negative impacts on marine biota and ecology (Cripps et al., 2013; González and Ilyina, 2016). Data are uploaded remotely to an online dashboard in real-time, enabling constant monitoring and quantification for process control, risk mitigation, and CDR certainty that is needed for deploying such interventions into natural systems at scale. Particularly by measuring the water chemistry after the CDR reaction, this batch-controlled, complete measurement approach to alkalinity addition can serve as a major component to a robust environmental impact assessment and risk mitigation strategy, easing social and regulatory barriers to adoption.

The efficacy of this closed system alkalinity addition approach is aided by specifically targeting high CO_2 waters (Fig. 2). Waters that have more than ~425 ppm CO_2 (current average global atmospheric concentration) are sources of CO_2 to the atmosphere due to air-sea equilibrium (Zeebe and Wolf-Gladrow, 2001). While much of the ocean is less than atmospheric concentration, absorbing CO_2 from the atmosphere, many coastal waters are characterized by lower pH and higher CO_2 due to the respiration of organic carbon from land, contributing between 0.5 - several gigatons of CO_2 emissions per year (Takahashi et al., 2009; Cai, 2011i, Breitburg et al., 2015; Tomasetti and Gobler, 2015). The East river in New York, the focus area of this project, has been shown to have CO_2 concentrations of >2000 ppm, and pH as low as 7 (over 1 unit lower than mean ocean) (Wallace and Gobler, 2021), making it an ideal setting to convert CO_2 to HCO_3 by adding alkalinity, reducing CO_2 bound for the atmosphere, with an ecological co-benefit of mitigating localized acidification. By measuring the removal of biogenic CO_2 from high-concentration natural waters in real-time, Vycarb's approach is distinct from other proposed ocean alkalinity projects that depend on an increase in the absorption of atmospheric CO_2 later (potentially months later; Zeebe and Wolf-Gladrow, 2001), with temporal and spatial variability inhibiting reliable MRV (Burt et al., 2021; He and Tyka, 2023; and outlined in (carbon)plan's verification framework).

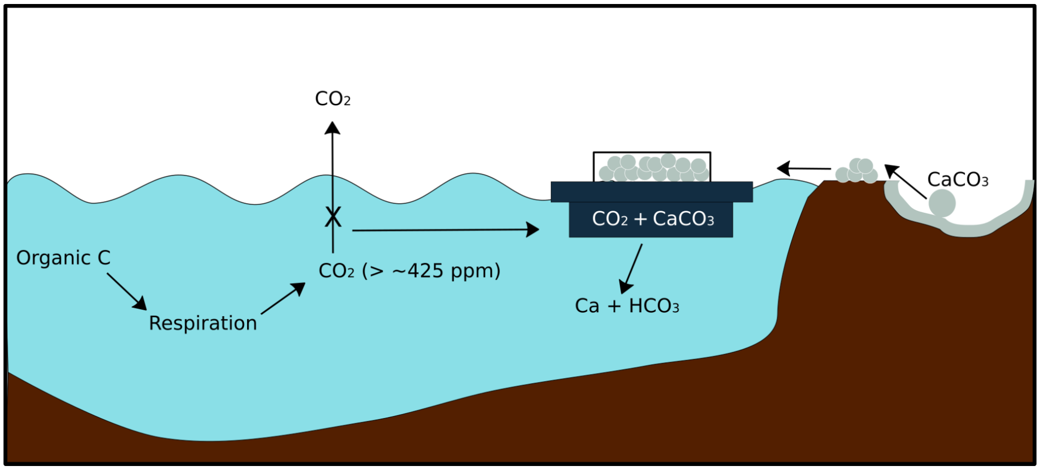

Figure 2: A simplified schematic showing the application of Vycarb's floating system [patent pending] (shown in dark blue) for removing elevated concentrations of biogenic CO_2 bound for the atmosphere, with long-term storage as stable dissolved inorganic carbon (e.g., HCO_3).

This precise, fully-measured approach to alkalinity addition will be deployed in a floating, modular system (Fig. 3) that can be moored, anchored, or docked to enable a decentralized approach for rapid global scale up. Results will enable the development of Vycarb's sensing technology and floating system for application in higher volume, continuous flow alkalinity addition, as well as in other ocean- and water-based CDR projects.

In the floating system, water is held in a fully-submerged containment to quantify baseline dissolved CO_2, HCO_3, and CO_3 conditions. The amount of pre-dissolved alkalinity added is controlled by the amount of dissolved CO_2 measured in the water containment. The water containment is measured throughout alkalinity addition, tracing the conversion of CO_2 to HCO_3 and CO_3. When alkalinity addition is completed, and before release of treated water, the final concentrations of CO_2, HCO_3, and CO_3, and pH are measured to quantify total CDR and confirm ecologically safe water chemistry (Cripps et al., 2013; González and Ilyina, 2016).

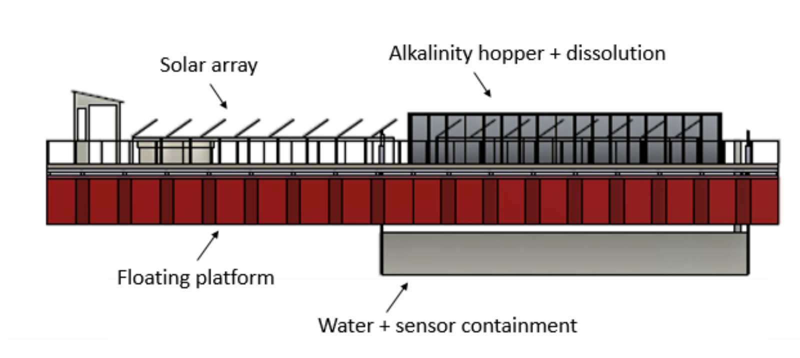

Figure 3: Simplified schematic of the floating system, with submerged water containment below [patent pending].

Vycarb has demonstrated this approach at a small scale in our planned project location, generating real-time, direct in-field verification of CDR by tracing all three dissolved inorganic carbon compounds (CO_2, HCO_3, CO_3) in natural waters before, during, and after alkalinity addition (Fig. 4). We are optimizing the measurement to improve accuracy and precision in these real-world settings. The floating system for this project was designed based on our experience from several small scale pilots.

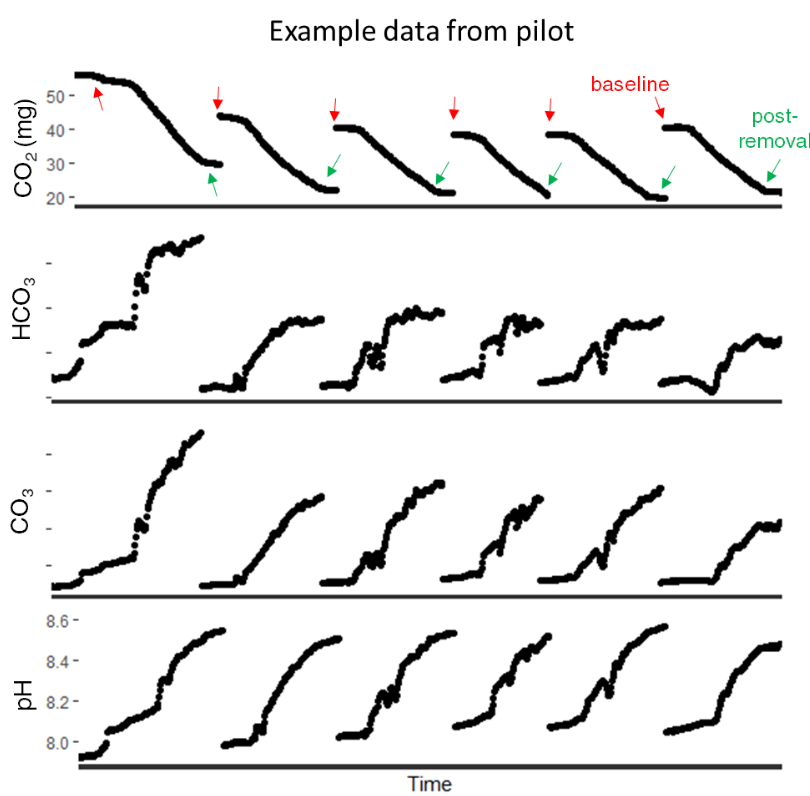

Figure 4: Example results from Vycarb's pilot deployments showing repeated batch treatment cycles that bring in natural water, add alkalinity ($CaCO_3$ was used in this test), and return treated water to the open water system (in this case, the Peconic Estuary).

Vycarb's mission is to empower the world with high-quality, high-impact carbon removal in three ways.

First, our integration of alkalinity addition with real-time MRV, once demonstrated and optimized, can generate high volume, fully-measured CDR in natural waters around the world. These modular, alkalinity-flexible systems can enable cost-effective deployment of alkalinity addition across a wide range of geographies, providing a pathway to scale up high quality CDR. The direct, full measurement of CDR efficacy and water chemistry impacts will reduce barriers to adoption compared to less controlled environmental interventions. We plan to own and operate many of these systems to continue to optimize and improve throughput.

Second, our advanced sensor technology is designed to enable other CDR project developers with low-cost, high-reliability verification through real-time measurement of dissolved CO_2, HCO_3, and CO_3. Our approach verifies the removal of CO_2 from water and resulting storage as stable HCO_3 and CO_3 with considerably higher certainty than modeling, and considerably lower cost than in-field sampling and subsequent analyses at scale. Given the high temporal and spatial variability of marine carbon cycling, continuous direct measurement is critical to support higher confidence of both CDR efficacy and ecosystem safety. This level of monitoring will also be particularly important to meet the rigor required in environmental impact assessments for permitting projects at scale. With ocean CDR's novelty, lack of field deployment, and public skepticism, Vycarb's direct measurement MRV will support ecologically safe, cost effective, and verifiable scaling across a wide range of water-based inorganic (i.e., HCO_3 and CO_3-driven) CDR.

Finally, we aim to provide our integrated measurement and CDR systems as a platform to enable owners and operators of existing water-facing infrastructure to generate high-value CDR. This decentralized enabling technology approach can accelerate the scalability of ocean-based CDR by leveraging existing ocean operations for deployment, rather than requiring single CDR project developers to permit and build infrastructure in new geographies. By empowering local communities with the tools to generate revenue from CDR, we aim to advance distributive justice of the industry more broadly, envisioning a world where a wide range of communities, companies, and sectors can contribute to and benefit from high-quality CDR.

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.

In this project, Vycarb will sequentially develop and deploy two floating carbon measurement and removal systems. The initial system will be capable of 12 tons/yr of CO_2 removal. The second, larger system will be capable of 95 tons/yr of CO_2 removal. Future, full-scale systems will be capable of up to 10,000 tons/yr. We have established the necessary partnerships to deploy these first systems in the East River, where low pH and high CO_2 conditions provide an ideal setting to demonstrate our approach to fully-measured CDR via alkalinity addition (Fig. 5). Deploying these systems over several years will not only generate high quality CDR, but will provide a detailed database and understanding of the impacts of alkalinity addition over a range of real-world conditions, which is critical for scaling up for higher volume CDR. Demonstrating and validating our measurement approach at the tons/year scale will also provide the detailed understanding needed for wider adoption and deployment of Vycarb's high-resolution, low-cost MRV for other water-based CDR projects.

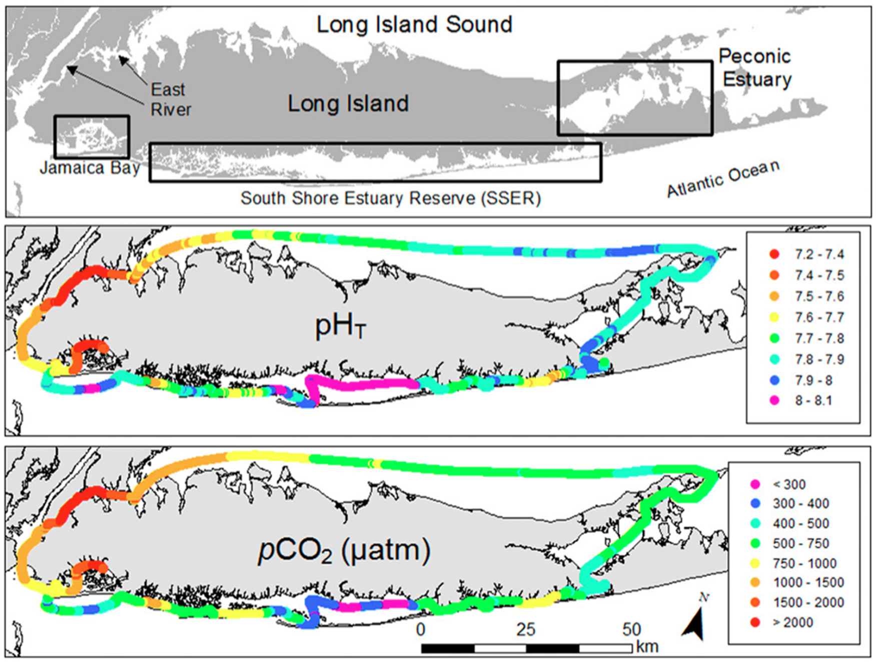

Figure 5: Survey data (from [Wallace and Gobler, 2021]) from the study area showing elevated pCO_2 > 2000 ppmv and pH below 7.4 (1 unit below mean ocean) in proposed project location.

To calibrate our measurement approach and quantitatively assess the impacts of alkalinity addition on the ecosystem and water quality at scale, Vycarb will collect regular (>100 per week initially, and at least >10 per week later in the project) comparison samples from within the device, and from the surrounding waters. The measurement system's performance will be benchmarked to traditional analytical methods using potentiometric titrations and other dissolved inorganic carbon analyses at independent laboratories. Those results will be used to optimize our technology over time, and published to demonstrate the performance of the in-situ measurement for broader adoption. The costs associated with these validations add to the net $/ton of this initial deployment, but will provide higher confidence and lower uncertainty for this measurement approach in the long run. Proxies for biological impacts such as pH, dissolved oxygen, chlorophyll-a, and organic carbon will also be measured to assess how this approach at scale affects ecosystem health.

We will use powdered $CaCO_3$ for this project, sourced from a regional agricultural limestone producer, for low material and shipping costs and input emissions. While the expected efficacy of $CaCO_3$ is ~4.5 tons per ton of CO_2, our system can use a range of materials, including those more effective (less material per ton CDR), when costs, input emissions, and availability allow. We enable the use of different materials by using a flexible mineral dissolution approach, and controlling the alkalinity addition based on its measured impact, rather than the theoretical potential of a certain mineral composition. This flexibility enables us to optimize each deployment for cost and input emissions at scale by considering the available materials for a given geography, and the preferred materials for a given region's communities and regulatory agencies.

The two systems for this project will be built using new materials under standard barge construction for an expected 30 year lifetime. Based on the insights from this project, we will optimize future builds to bring down capital costs and increase efficiency, including larger tank size, lower materials cost, and development of this system for continuous-flow, higher-volume alkalinity addition, rather than the slower batch treatment approach of these first systems. While this project's systems will have water containment sizes of 50,000 and 200,000 liters, we plan to continue to increase size with subsequent builds towards an ultimate goal of 2.5M liters (volume possible using standard barge dimensions) at continuous flow, to achieve up to 10,000 tons of CDR per system per year. Thus, while our first system in this project will achieve 12 tons per year at relatively high capital cost, we will leverage this deployment to develop a system capable of removing thousands of tons of CO_2 per year with lower relative capital costs, bringing amortized capital cost for the floating system down from hundreds of dollars to <$5 per ton at scale.

This project delivers three additional outcomes that are critical to accelerate the delivery of ocean-based gigaton-scale CDR at lower cost.

First, the information developed in this project will enable development of a larger, lower-cost system for higher throughput CDR that can deliver at under $100/ton using a wide range of materials. This system also creates a pathway towards high-volume CDR delivery using a decentralized deployment strategy, coupling to existing water operations, which at scale can reach 0.5 Gt/year with lower barriers to adoption compared to centralized, single-plant infrastructure. Our current techno-economic analysis indicates that CDR costs below $60/ton are achievable at scale.

Second, the deployment of our real-time in-situ measurement system at a relevant scale and throughput will accelerate its adoption in other water-based CDR and storage projects, reducing costs of MRV while increasing confidence by providing an autonomous, in-field, low-cost direct measurement. Existing methods for verifying and assessing CDR efficacy require prohibitively expensive sensors, field sampling, and in-lab analyses that fail to provide the level of confidence and temporal resolution needed to quantify exactly how much carbon dioxide is converted to stable forms. Direct, continuous measurements also enable process optimization, particularly to the changing conditions in a natural system each day, season, and over time. By demonstrating the utility of an automated, low-cost measurement, this project will support reduced cost MRV and thus reduced operational costs over a wide range of other CDR approaches for faster scale and greater impact.

Finally, data generated from this project will help to accelerate the safety, efficacy, and verification of alkalinity-based CDR generally, by providing detailed real-world data tracing the kinetics and impacts of calcium carbonate addition to high CO_2 waters over several seasonal cycles. While Vycarb's measurement approach is proprietary, the data we generate in this project is not, and we will share results openly to demonstrate the validity of this approach for CDR, and inform deployment of other

strategies. Given the lack of public trust particularly around ocean interventions, where ecosystem health and unintended consequences are likely without proper care, this data will accelerate the development of safe and effective approaches to water-based CDR more broadly, and enable gigaton scale deployment more rapidly.

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.

[public answer]

Risk	Mitigation Strategy
Financial Risk: Materials cost change through time	Our approach can use a wide range of alkaline minerals. Each material's availability, cost, input emissions, and efficacy ranges widely, and may likely change significantly over time, introducing some risk to forecasting costs in the future. In this project, we will use $CaCO_3$, which requires ~4.5 tons to remove one ton of CO_2. For other materials, greater weight percent of alkalinity drives higher CDR potential, but high costs currently make those materials less desirable. As markets develop, some materials may become more available (via new technologies) and attractive (via utility in carbon removal markets), and the per ton cost may go up for some and down for others. We are currently testing seven different kinds of alkaline materials across the spectrum of dissolution rates (oxides, hydroxides, carbonates, and silicates: MgO, $Mg(OH)_2$, $MgCO_3$, Na_2CO_3, CaO, $CaCO_3$, basalt), enabling the use of the most economical, readily available, and low-emissions alkalinity in any location. This strategy also positions us to successfully partner with other companies who generate these materials and are looking for opportunities to deploy them in a safe, effective, and measurable way.
MRV Risk: Measurement device underperforms/ fails	While our measurement technology has been validated at our current scale using independent sampling and analysis by potentiometric titrations, we are continuously optimizing this relatively new technology for improved performance. Once applied to this projects' scale, the measurement system may require further optimization. We will perform frequent manual sampling (>100 per week for the first several weeks, down to 10 per week once validated within ideal range) and in-lab analysis to calibrate measurement results and provide independent assessment. 1. If the automated measurements are offset from laboratory measurements (i.e., beyond analytical error of titration, e.g., ~10 mg/L for HCO_3), we will make appropriate modifications to the measurement hardware and continue independent sampling procedures until automated measurement calibration meets analytical error similar to traditional measurement approaches. 2. If the automated devices fail to operate in total (i.e., stop working), our engineering team will identify the failure immediately, as all data is

	transmitted via cell service in real-time to our online dashboard, and fix the issue. We can easily exchange for new sensors in the case that any break or fail to perform at required specifications. 3. If the proven-out measurement approach fails to work at the scale of the next build (i.e., from 70 liters to 50,000 liters), we will increase the density of sensors per unit to enable accurate measurement across the total water volume. In addition, we have taken several steps to modify the measurement approach in this project's larger systems, relative to our small-scale pilots, to ensure that they perform at equal or better specifications at larger scale.
Technical Risk: Analytical longevity underperforms	Vycarb has established the utility and ruggedness of our proprietary inorganic carbon measurement technology via initial field testing, where it has been demonstrated across conditions (rain, snow, freezing, hot, salt water). Still, due to its novelty and deployment in harsh ocean environments, there is a significant requirement for thorough testing and validation throughout extended deployment. This project will provide dozens of instrument-years of real-world testing to determine mean time between failure (MTBF) and iterate instrument design and packaging to maximize instrument longevity in harsh ocean environments. We anticipate multiple cycles of instrument and packaging modifications over the course of this project to achieve the longevity required for low-cost, reliable, accurate measurement performance in harsh coastal environments.
Ecosystem Risk: This environmental intervention generates negative ecological impacts	As with all environmental interventions and novel environmental management practices, uncertainties around unintended ecological consequences must be constrained with careful continuous monitoring. Our strategy of partnering with ecosystem management agents (e.g., municipal conservation agencies, commercial aquaculture farms), and starting with this stepwise scaling approach for detailed ancillary monitoring, enables robust assessment of the ecological impacts at the site of deployment and downstream. In the case of observed unintended consequences (e.g., if we detect changes in water chemistry conducive to ecosystem harm or carbon-emissions), we will be able to remotely halt all operations, and leverage the collected data to identify and eliminate the causes.
Project Execution Risk: Permitting and regulatory frameworks prohibit deploying this system in some locations	There are many uncertainties around permitting ocean-based CDR, particularly given its nascence and the understandable skepticism from many communities and agencies around environmental interventions, and the potential for unintended consequences. Particularly for permitting, the variability in jurisdictions and policies across municipalities, states, and countries presents a significant risk to any ocean intervention, our approach included. However, Vycarb's technology, processes, and scaling strategy are specifically designed to mitigate this risk. For example, permitting the discharge of altered water from floating vessels is standard - and while there are often restrictions on locations for vessel water discharge, the existing frameworks provide boundaries to plan within. Furthermore, having an entirely mobile system (i.e., floating platform, not permanently affixed to any hard or

soft structure) reduces many of the regulatory constraints met by other marine CDR projects. And the real-time measurement of treated waters before release provides a lower-cost, higher-confidence environmental impact assessment built into the deployment. Finally, our ultimate goal - to provide enabling technologies for other, existing water-based operations to generate CDR - has the additional benefit of working within existing operational permits. We will use this project, with our range of partners, to design and plan our scaling strategy further to ensure that this risk is mitigated for our particular technology.

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

Proposed CDR over the project lifetime (tons) *(should be net volume after taking into account the uncertainty discount proposed in 5c)*	219 net metric tons (see 4d) * 16% uncertainty discount = 184 metric tons
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	August 2027
Levelized Price ($/ton CO_2)* *(This is the price per ton of your offer to us for the tonnage described above)*	$2,174 ($400,000 / 184 tons)