CREW

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

CREW

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

New Haven, CT

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

Dr. Joachim Katchinoff; Lydia Jackson

Brief company or organization description

CREW is a distributed and flexible carbon removal technology that uses containerized enhanced weathering for permanent and verifiable storage.

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.

Developed by researchers at Yale's Earth and Planetary Sciences Department and the Yale Carbon Containment Lab (CCL), CREW utilizes containerized enhanced weathering (EW) for permanent, low-cost, and verifiable storage (Fig. 1). This approach accelerates the well-established weathering process in an engineered reactor system for rapid and verifiable CO2 capture.

[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.

Natural weathering occurs with silicate rocks for removal on geologic timescales, and with carbonate rocks for removal on timescales of ~10,000 years. By 1) increasing the reactive surface area of the rocks through milling them to a powder (see Beerling et al., 202, NAS, 2019, Strefler et al., 2018,) and 2) exposing these powders to water and CO2, EW safely and rapidly stores large quantities of CO2.

Containerized EW as a CDR technology has multiple use cases, including CO2 removal and storage from wastewater treatment processes. This technology can also store carbon from a range of CO2 sources, like Biomass with Carbon Removal (BiCR) and direct air capture (DAC). Finally, it can operate as carbon capture and storage for hard-to-mediate point source emitters.

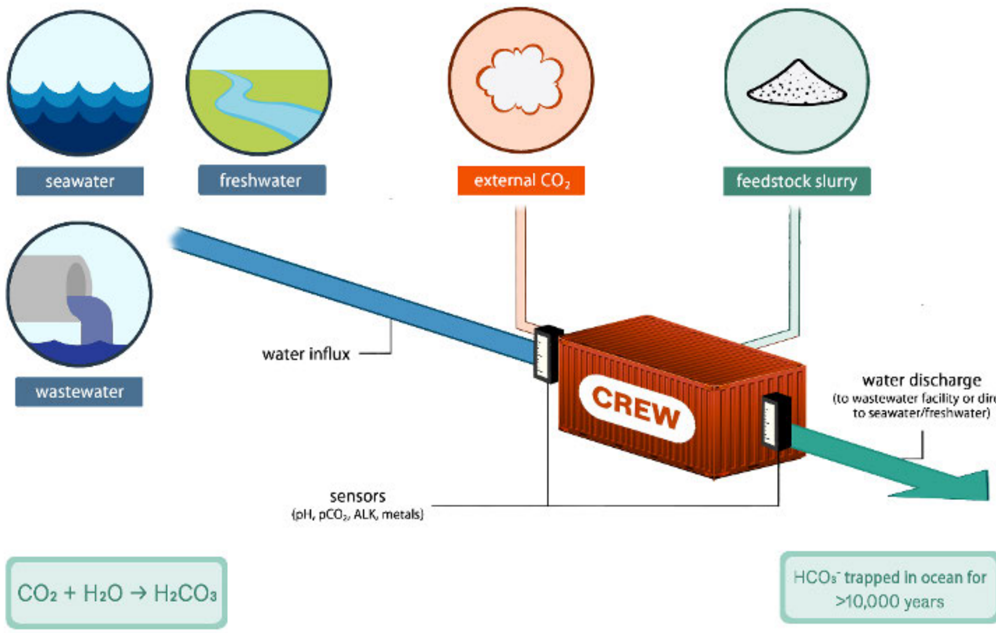


Figure 1. Schematic of CREW's containerized EW unit, which contacts CO2-consuming feedstock with CO2-bearing fluids in a reactor or series of reactors to promote weathering reactions in a controlled and monitored setting.

The CREW process works by building from the basic aspects of carbonate chemistry. CO2 rapidly equilibrates with water, dependent on the temperature and CO2 partial pressure:

CO2(g) <-> CO2(aq) (Eq 1)

The amount of CO2 that will dissolve into water is proportional to the partial pressure of the gas in the system. When more CO2 is added to the system, more will dissolve, forming carbonic acid. This will then reduce the pH of the water:

CO2(aq) + H2O(aq) <-> H2CO3(aq) (Eq 2)

Depending on the chemistry of the water, the species of carbon will be portioned as carbonic acid, bicarbonate, and carbonate ion:

CO2 + H2O <-> H+ + HCO32- <-> 2H+ <-> CO32- (Eq 3)

Carbonic acid will react with naturally occurring rocks:

XSiO3(s) + 2CO2(aq) + H2O(aq) <-> X(aq) + 2HCO3-(aq) + SiO2(aq) (Eq 4)

XCO3(s) + CO2(aq) + H2O(aq) <-> X(aq) + 2HCO3-(aq) (Eq 5)

where X represents a divalent cation (e.g., Ca2+, Mg2+, Fe2+). During this weathering process, the rock is dissolved, transforming carbonic acid into the bicarbonate ion (HCO3-). Within bicarbonate, the carbon is trapped and can no longer easily re-release to the atmosphere. These dissolved ions will eventually reach the oceans via river water or groundwater, where the carbon in bicarbonate will be trapped for >10,000 years as it cycles through the oceans (Middelburg et al., 2020; Renforth and Henderson, 2017; Berner, Lasaga, and Garrels, 1983). Depending on the end pH of the water stream leaving our reactors, there may be some loss of carbon when it is mixing with the oceans—however, we will quantify the impact with regional ocean models, earth systems models, and targeted sampling.

Most mineral weathering rates are highly dependent on pH; for example, limestone and olivine dissolution rates are multiple orders of magnitude larger at low pH than at high pH (Palandri & Kharaka, 2004). Under higher partial pressure CO2 conditions, weathering rates and thus CO2 capture rates are faster. With increased surface area due to milling, we achieve weathering rates and a means of CDR that are relevant to human timescales.

The CREW process (Fig. 2) starts with CO2 incorporated into water as carbonic acid. The CO2 can be added either naturally (e.g., from the atmosphere or from organic matter degradation), or through injecting water with an external CO2 source (e.g., from biogenic waste incineration or direct air capture). That carbonic acid is pumped through the CREW system, mixing and reacting with a crushed mineral feedstock to convert and store CO2 as dissolved bicarbonate alkalinity. This water is then discharged as effluent. For our project, the incoming influent is already charged with CO2 from organic waste sludge incineration (see below). As it is pumped into our reactors, it passes through the inlet sensor array, where components of the carbonic acid system (pH, CO2, alkalinity) are measured or sampled to provide us with the starting chemistry. The influent then passes through a bed or series of beds of medium- to coarse-grained limestone. During water-rock contact, weathering reactions dissolve the limestone and convert CO2 to HCO3-. Water then leaves the reactor and passes through the outlet sensor array, measuring ending chemistry and allowing us to quantify the amount of CDR. To optimize CDR, a series of controls are in place. For example, flow can be recirculated, flow rate can be modulated, additional feedstock can be added, and the feedstock bed can be agitated. This system has been tested and vetted at the lab scale, with experimental bench-top analyses, built prototypes, and reactive transport modeling. Our at-scale reactors will be modular: similar to DAC deployments, each base unit will be a modified, commercially available shipping container. This allows us to easily adapt to varying deployment sizes and ensure that the reactors tie into existing manufacturing and transportation infrastructure.

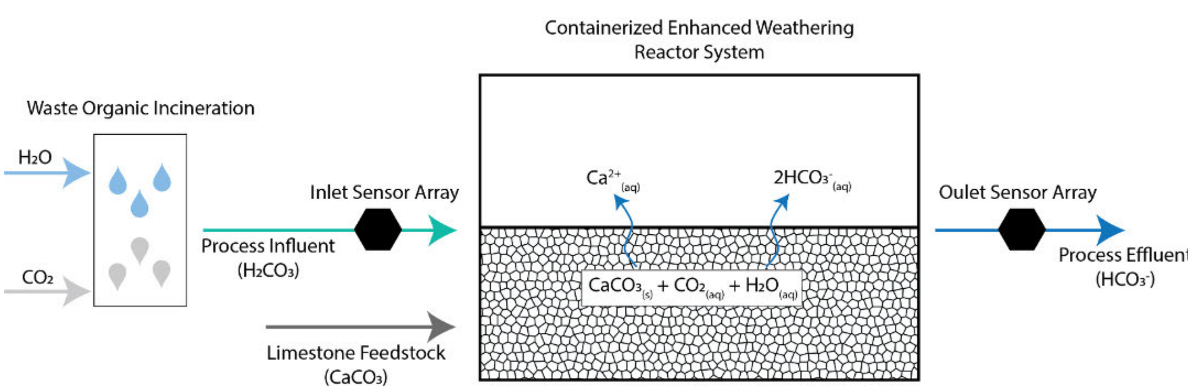


Figure 2. Schematic of containerized EW process flow diagram for pilot project.

Unlike EW in diffuse settings (agricultural fields or marine applications, for example), CREW deploys this carbon removal technology in reactors. It can therefore use existing infrastructure for channelized and permitted water flows. With sensors installed at the inlet and outlet of our system, we can monitor the chemistry of the fluids, and we can easily and accurately quantify the amount of CO_2 stored. For example, because carbon species in fluids are related by four equations:

Alkalinity = $[HCO_3^-] + [2CO_3^{2-}] – [H^+]$ (Eq 6)

Dissolved inorganic carbon = $[CO_2] + [HCO_3^-] + [CO_3^{2-}]$ (Eq 7)

$K_1 = [HCO_3^-][H^+]/[CO_2]$ (Eq 8)

$K_2 = [CO_3^{2-}][H^+]/[HCO_3^-]$ (Eq 9)

we can solve the entire system if at least two parameters are measured and acceptable assumptions are made about dissociation constants (K_1 and K_2), temperature, salinity, and pressure. Therefore, with relatively simple sensor technology to measure pH, alkalinity, and/or CO_2, we can quantify the conversion of carbonic acid to carbonate alkalinity and thus the amount of CDR across our process.

Mineral weathering on land is limited by the availability of minerals for dissolution and of water, given that the weathering reaction occurs in aqueous solution. The vast quantities of wastewater make it an obvious first target for CREW. Globally, about 95 trillion gallons of wastewater are produced annually, with the U.S. accounting for approximately 20% (Seiple et al, 2017). Wastewater infrastructure in the U.S. channelizes and concentrates large volumes of water to discrete locations for treatment. Furthermore, wastewater is ideal for CREW because of the relatively high carbon content of the water and the low concentrations of other chemical constituents that could cause back reactions (Cai and Jiao, 2022). As the CREW process raises the pH of wastewater, it provides added economic, ecological, and climate benefits by replacing the use of lime (CaO; therefore avoiding associated emissions). This process may reduce N_2O fluxes and can also reduce nutrient loads in wastewater effluents (by leading to more quantitative nitrification at higher pH).

CREW's first deployment targets removing CO_2 from municipal waste processes, specifically waste organic sludge incineration. During the wastewater treatment process, organic waste carbon that is not re-mineralized is collected and disposed of either through sale as fertilizer, removal to landfill, or incineration (Seiple et al., 2017). Like BiCR, during incineration the organic waste is converted to CO_2, creating a flue gas. This gas stream is quenched by wet scrubbing processes (Cooper and Alley, 2015; Turovskiy and Mathai, 2006), forming an acidic waste fluid, rich in CO_2, which degasses to the atmosphere under business-as-usual conditions. Significant amounts of organic waste carbon are incinerated across the US and the globe; for example, assuming ~15% of solid waste from wastewater treatment is incinerated in the US (Seiple et al., 2017), ~3 – 4 million tons of CO_2 could be captured per year. In Europe, ~200 million tons of CO_2 could be captured annually from waste incineration from multiple sources including wastewater sludge (Rosa, Sanchez, and Mazzotti, 2021).

Beyond CDR for municipal and industrial wastewater, CREW can operate as an alternative CO_2 storage process (Fig. 3). Provided accessible water, CREW can store CO_2 from any source and at any concentration. This includes carbon from BiCR, DAC, and point source emitters. CREW's flexibility and impact is because 1) our process can demand a lower purity CO_2 feedstock to create a relatively rich CO_2 fluid, reducing the need for costly CO_2 purification, and 2) we can co-locate with CO_2 sources, reducing the need for significant infrastructure required for underground storage. In summary, CREW can act as a permanent CO_2 endpoint that is easily measurable, with relatively low infrastructure requirements, and with faster deployment relative to geological storage. Because of its varied use cases, CREW can enable a broad range of carbon capture methods as low-carbon, low-cost energy becomes more available in the next several decades.

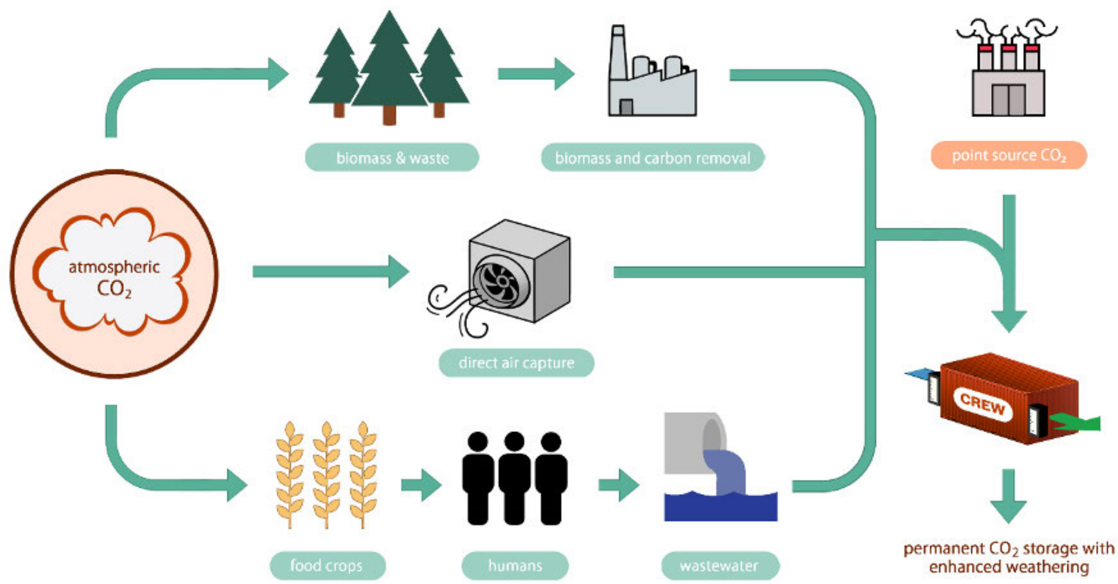


Figure 3. CREW's use case strategy and areas of impact.

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.

CREW is currently at TRL 6. We have tested representative models of the system by 1) running bench-scale experiments using actual samples from the field and with CO2-equilibrated fluids to recreate a relevant environment, 2) building and testing prototype containerized EW systems to inform pilot-scale system design and fabrication, and 3) conducting geochemical reactive transport modeling informed by theory and literature as well as by results from laboratory experiments. Finally, we have worked with in-house and external engineering experts to design and implement a prototype system to achieve CDR in the field. We are following steps to achieve TRL 7 (prototype in an operational environment) by October 2022 and anticipate achieving this level of readiness by the end of 2022.

With these data, we are preparing a scientific manuscript for peer-reviewed publication.

Additional information in the confidential addendum.

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?**

Reaction kinetics	1×10^{-6} t CaCO3 dissolved/liter influent	1×10^{-6} t CaCO3 dissolved/liter influent	This value for our NOAK system is likely conservative, and we anticipate that this number will be higher in NOAK systems. However, this value is dependent on influent chemistry (CO2 source, alkalinity, acidity, hardness) and water flux accessible to our system.

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?

The CREW technology grew from research by Dr. Joachim Katchinoff and Professor Noah Planavsky in the Earth and Planetary Sciences Department (EPS) at Yale University and was catalyzed by the Yale CCL. Our nine person team has technical expertise in geosciences, engineering and ecology, as well startup, commercialization, carbon credits, and investments experience.

The CREW team includes Dr. Joachim Katchinoff, whose current research is on negative emissions technologies, specifically carbon removal via enhanced weathering. He has seven years' experience applying geochemical and experimental tools, including novel metal isotope systems and numerical modeling, to investigate the role of weathering reactions in the global carbon cycle. Dr. Ella Holme specializes in experimental geochemistry related to the carbon cycle in Earth's geologic record. Her expertise is primarily in the development of novel experimental techniques to answer complex questions about climate, carbon, and the geologic and chemical processes that control them. Jeffrey Grant has 10 years of experience designing and implementing bespoke software and sensors systems in autonomous, field-deployed instruments. He has worked in collaboration with scientists at Woods Hole Oceanographic Institute and Yale University.

The CREW team is supported by Professor Noah Planavsky (EPS), Justin Freiberg (CCL), Dr. Anastasia O'Rourke (CCL), Dr. Sinead Crotty (CCL), Dr. Abby Lunstrum (CCL), Lydia Jackson (CCL), and Dean Takahashi (CCL). CREW has also engaged a CT-based environmental law firm, a WA-based environmental law firm, an engineering firm, a firm with milling expertise, a wastewater engineering expert, and a life cycle assessment expert.

The CREW team is growing and is in the process of hiring a geoscientist, mechanical and chemical engineers, and a business operator.

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
Greater New Haven Water Pollution Control Authority	Project site operators	Confirmed partner
Woodard & Curran	Engineering design expertise	Confirmed supplier
Yale Metal Geochemistry Center	Analytical expertise and laboratory resources	Ongoing collaborator
Yale CCL	Research and management support	Ongoing collaborator

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?

The project timeline will be from October 2022 to December 2023. CDR will be generated by our prototype system while we design and fabricate our FOAK system.

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 for this project will occur from November 2022 to December 2023. The reaction rate of our feedstock interacting with the CO2-rich influent stream is predicted by completed geochemical modeling and analytical work (see 1a-b). Given 1) the accessible flow of CO2-rich influent, which is produced continuously at our partner site, and 2) the water flux that can be accommodated by our containerized enhanced weathering system, we predict that CDR will be constant. There will be downtime associated with maintenance and upgrades to our system and our partner site; however, downtime should be minimal (6 weeks or less).

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	200 tons
2024	30,000 tons

2025	75,000 tons
2026	105,000 tons
2027	147,000 tons
2028	191,000 tons
2029	248,000 tons
2030	322,000 tons

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	Installation of field prototype system at project site	Q4 2022
2	Testing of monitoring array, automatic controls, and data collections and management systems	Q4 2022
3	First ~15 tons of CO2 capture by prototype system, which will show that our system can operate continuously for a month and offer a clear path to reaching annual capture goals	Q4 2022 - Q1 2023
4	Installation of FOAK system	Q2 2023

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

Patents will enable the protection and scaling of the CREW system in the U.S. and in other countries where the system may be deployed. As such, in August of 2022, we filed an international patent application under the Patent Cooperation Treaty (PCT). We will soon be filing a non-provisional patent application in the U.S. through the Climate Change Mitigation Pilot Program. We will then file non-provisional patent applications in countries we will target for deployment of CREW.

These patent claims will protect systems and methods pertaining to our CO2 capture strategy, and a wide range of design iterations, feedstock types, and application potentials for the CREW system to durably capture and store carbon.

As we move forward with CREW, there is potential for this IP to be licensed to partners.

k. How are you going to finance this project?

The CREW systems have a relatively low upfront capital expenditure. We are financing the engineering and construction of the project with funding already received from the Grantham Foundation and others. Equipment and operating costs (feedstock, transportation and on-site employees) will be partially offset through cash flows generated by the selling of carbon credits.

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.).

We do not have nor do we intend to actively pursue other CDR buyers for the project timeframe.

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.

For this CDR project, we are not expecting additional revenue streams in the near term.

For future revenue, we are exploring whether 45Q tax credits could apply to CREW's CDR and storage strategies, especially if combined with DAC or BiCR for CO2 inputs. Other revenue may include payment for treating low pH wastewater from different facilities, replacing the need to add lime (so long as it does not interfere with additionality claims for CDR credit sales). In addition, we are exploring metal recovery options with olivine and ultramafics, but this is still in the experimental phase.

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
Technical: Under field conditions, kinetics of weathering rates are not as predicted by modeling or experimental work (Medium).	Because we are aiming to initially use larger grain sized feedstock, we could adapt by sourcing finer milled feedstock (thus increasing reactive surface area) or altering reactor operation to optimize water-rock interaction.
Technical: Under field conditions, sensors will be more easily damaged and need frequent replacement (Low).	We have done extensive testing of sensors in laboratory settings, simulating field conditions as closely as possible, and sensor lifetime has been as expected. However, we will have backup sensors along with other monitoring techniques such as hand sampling ports for sample processing in our labs.
Operational 1: Equipment and/or feedstock deliveries are delayed due	We plan to order equipment well in advance and arrange storage with the project facility on site, including a back-up plan for storage at Yale's West-Campus. We will outline all steps and requirements needed to

to supply chain/shipping or delivery issues (Medium)	make and take delivery on site and plan to be in frequent communication with suppliers.
Operational 2: Operating during extreme or variable weather conditions. (Medium)	Our system can easily be taken offline and restarted - an operator would only need to take the pumps offline and drain the reactors. Additionally, the incoming waste stream from the organic matter sludge incinerator is warmer than ambient temperature thus minimizing the risk of frozen pipes during cold temperatures.
Management: Engineering recruits take longer to secure or do not perform as expected (Medium)	Identify candidates and conduct a wide search for exceptional engineering talent to join the team. We aim to ensure compensation meets market rates and will work with new recruits to provide clear direction and oversight. Additionally, we may work with an existing contract engineering team to provide back up and additional engineering support if needed.
Financial: More funds are needed to purchase equipment or feedstocks given recent transportation price increases and supply chain issues (Low)	We have secured sufficient funds to pay for the project through direct, dedicated grants and have made conservative budget estimates based on real pricing. We are in frequent communication with suppliers and are tracking project funds carefully. Project funds are dedicated to the project and cannot be used for other projects.
Ecosystem: Measurement of ecosystem impacts proves difficult given constraints of working with multiple agencies in the Long Island Sound (Low)	We have begun engagement with existing groups monitoring the ecosystem baseline conditions in New Haven Harbor near the site of the effluent stream. We have designed a study and are developing a detailed protocol for data collection to prove minimal disturbance. It will measure all permitted effluents as well as other factors of potential interest to local environmental organizations, state policy, and local shellfish industries.
Health and Safety: Moving heavy and fine feedstock materials, while benign, could pose an OH&S risk (Medium)	Clear protocols for handling materials are being developed, including using PPE and ensuring ergonomic equipment if available. OH&S and Safety training will be required by all onsite technicians and team members according to the facility's specifications. This is being reviewed and will be supplemented as needed to ensure safe handling of fine materials. All fine materials will be covered.

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?

Our approach is grounded in the idea that we are directly tracking the conversion of carbonic acid into bicarbonate. In our first pilot project, the bicarbonate generated by our system will be directly discharged into the ocean after passing through our partner site's wastewater system. With decades of sampling and modeling, there is consensus that the residence time of bicarbonate in the oceans is on the order of 10,000 years or greater (e.g., 88-121 kyr Middelburg et al., 2020; 100-1,000 kyr Renforth and Henderson, 2017), which is effectively permanent from a human time scale. However, over a >10,000 year interval some of that bicarbonate will be converted to calcium carbonate—rereleasing CO2 to the atmosphere. We will directly track that conversion using the Earth System model, cGENIE (Ridgewell and Zeebe, 2005; Adloff et al., 2021), using an already established model pipeline for enhanced point source alkalinity addition (e.g., similar to riverine input). cGENIE is an ideal tool since it has a robust representation of the carbonic acid system in marine settings. Moreover, it is computationally inexpensive (relative to CMIP class GCMs), allowing for multiple 1,000 years runs via cluster computing. We will use this same modeling framework to estimate any possible carbon loss during carbonic acid system reequilibration when our discharge stream mixes with seawater and cycles through the oceans over thousands of years.

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?

There are limited durability risks associated with our process. If the effluent from our system is discharged with a pH less than 6.5, there may be loss of CO2 that was converted to bicarbonate during weathering as well as degassing from the initial CO2-rich influent stream as it equilibrates with the atmosphere. However, one of the appeals of having engineered, containerized weathering —with remote monitoring—is that the system can be optimized by changing flow rates, feedstock sizes, water-rock ratios, and flow recirculation to ensure more complete removal of CO2 from the influent and ensuring pH is at an optimal range for discharge.

Once CO2 is converted to bicarbonate, the carbon cannot easily re-release to the atmosphere; furthermore, CO2 stored with EW cannot be mismanaged when discharge is directly to large waterways.

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	215 tons CO2 captured
Describe how you calculated	Geochemical modeling informed by laboratory data indicates that our

that value	system can consume 1.63 t CaCO3 per day at a flow rate of 18,000 gallons per hour. Given that carbonate consumes CO2 at a ratio of ~0.4 t CO2/t CaCO3 (see Renforth, 2017; e.g., CaCO3(s) + CO2(aq) + H2O(aq) -> Ca2+(aq) + 2HCO3-(aq) means 44.01 g/mol CO2 is consumed stoichiometrically per 100.087 g/mol CaCO3): 0.4 t CO2/t CaCO3 x 1.63 t CaCO3 = 0.65 t CO2 capture/day. Extrapolating to annual capture assuming an annual capacity of 90%: 0.65 t CO2/day x 365 days x 90% = 215 tons CO2 captured. While CDR will occur from November 2022-December 2023, we are calculating a year of full-scale CDR to account for ramp up of the system and downtime. As delineated in 1n, there is remaining uncertainty surrounding reaction rates under field conditions as well as operational risks from our partner site that could lead to longer project downtime.

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.

To date, we have been operating our prototype system at the laboratory scale, which is significantly smaller than our project deployment. During system development and prolonged testing, we have captured 98 kg CO2.

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 not include this number in your gross or net CDR calculations; it's just to help us understand potential co-benefits of your approach.

For our project, we are targeting the acidic waste stream generated by organic waste sludge incineration. As lime is sometimes used to neutralize acidic streams, there are potentially avoided emissions from replacing this process. Nitrification rates are less efficient with lower pH, which leads to more production of N2O, a potent greenhouse gas. Therefore, CREW potentially will reduce N2O emissions by preventing the discharge of the acidic waste stream back into normal wastewater operations (which is commonly done to increase pH). Finally, given the increased carbonate alkalinity concentration in the effluent of our process, the ultimate discharge of our effluent to marine settings also combats the effects of ocean acidification at the local scale.

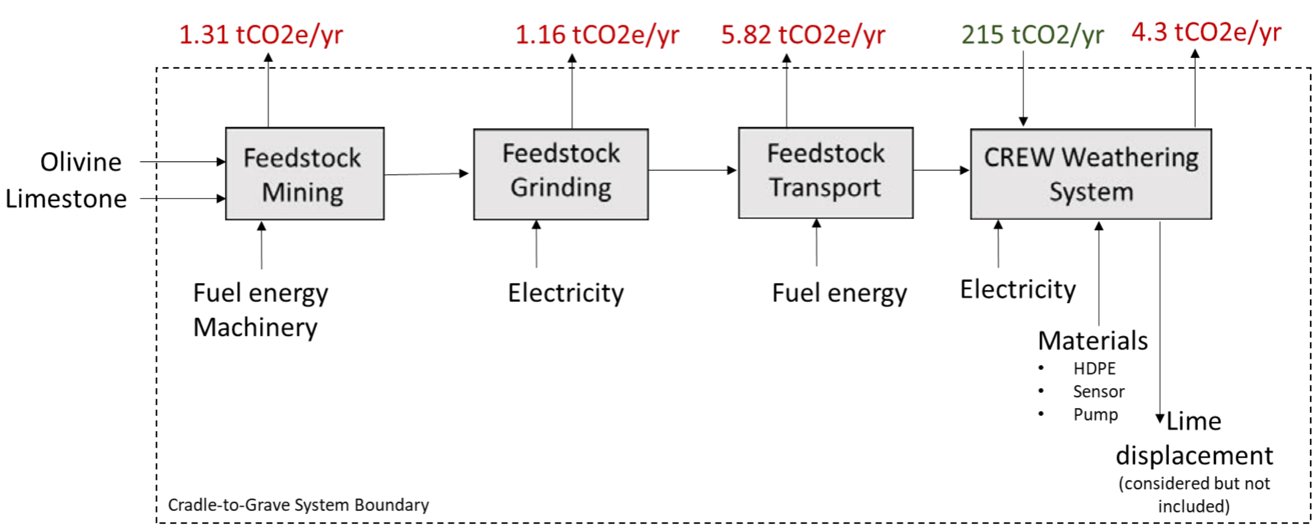
d. How many GROSS EMISSIONS will occur over the project lifetime? Divide that value by the gross CDR to get the emissions / removal ratio. Subtract it from the gross CDR to get the net CDR for this project.

Gross project emissions over the project timeline *(should correspond to the boundary conditions*	From our LCA modeling, we anticipate gross emissions due to feedstock mining

described below this table)	and milling, equipment fabrication, water pumping, and sensor operation to equal ~12.6 t CO2e/yr.
Emissions / removal ratio *(gross project emissions / gross CDR–must be less than one for net-negative CDR systems)*	Removal ratio = 12.6 t CO2e emission/215 t CO2 capture = 0.0586
Net CDR over the project timeline *(gross CDR - gross project emissions)*	Net CDR = 215 t CO2 captured - 12.6 t CO2e emissions = 202.4 t CO2 captured As our modeling suggests, the extent of leakage will be dependent on pH of discharged fluid. We will take this into account when predicting net long-term CDR, and assume a long-term leakage effect of a 10% inefficiency.

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:

- The LCA scope should be cradle-to-grave
- For each step in the PFD, include all Scope 1-3 greenhouse gas emissions on a CO_2 equivalent basis
- Do not include CDR claimed by another entity (no double counting)
- For assistance, please:
    - Review the diagram below from the CDR Primer, Charm's application from 2020 for a simple example, or CarbonCure's for a more complex example
    - See University of Michigan's Global CO_2 Initiative resource guide
- If you've had a third-party LCA performed, please link to it.



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?

The LCA system boundary extends from cradle to grave. It includes extraction of the mineral feedstock resources and other inputs, emissions associated with transport of inputs, crushing/grinding and other intermediate processing of inputs, equipment fabrication, and emissions from operating CREW. The system boundary could further include potential displacement of emissions from avoided lime or other alkaline amendments typical in wastewater treatment systems; however, we have not directly factor this into our LCA analysis.

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.**
Feedstock mining	1.31 tCO2e/yr	Emissions estimated assuming open pit mining which includes drilling, blasting, excavation. Excavators, drillers, and dumpers are assumed to be diesel driven. Emissions factors and impacts from DOE's Mining Industry Energy Bandwidth Study, 2007.
Feedstock grinding	1.16 tCO2e/yr	Emissions estimated from energy required to grind feedstock to 500 microns. Emissions factors from electricity used to grind from Thinkstep AG 2019: GaBi and industry based, official LCI datasets from thinkstep, "U.S. Life Cycle Inventory Database." National Renewable Energy Laboratory, 2012, and EPA's GHG Emissions Factors Hub.
Feedstock transportation	5.82 tCO2e/yr	Emissions estimated for truck transportation from limestone quarry to project site. Emissions factors for fuel energy from direct transportation quotes, Thinkstep AG 2019: GaBi and industry based, official LCI datasets from thinkstep, "U.S. Life Cycle Inventory Database." National Renewable Energy Laboratory, 2012, and EPA's GHG Emissions Factors Hub.
Fabrication and operation of CREW system	4.3 tCO2e/yr	Emissions estimated from fabrication of CREW system, based on reactor, sensor, controls, and pump materials. Emissions estimated from operation of CREW system based on electricity inputs for operating pumps, sensors, and controls systems. Emissions factors from

		materials fabrication are from EPA's GHG Emissions Factors Hub. Emissions factors from electricity from Thinkstep AG 2019: GaBi and industry based, official LCI datasets from thinkstep and "U.S. Life Cycle Inventory Database." National Renewable Energy Laboratory, 2012.

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.

A strength of our approach is that monitoring, reporting, and verification are relatively straightforward compared to almost all other forms of enhanced weathering. By using containerized and engineered reactor systems, we can directly track two components of the carbonic acid system in both the influent and the effluent stream using standard sensors. This allows us to solve all six components of the carbonic acid system, including CO2 concentrations (see Zeebe and Wolf Gladrow, 2001, as well as 1a for methodology and assumptions). In this project, we will be 'over' monitoring by conducting continuous and autonomous pH and CO2 measurements occurring every 10 seconds and 5 minutes, respectively, as well as sampling for alkalinity titrations every 30-60 minutes. The difference in CO2 concentrations and corresponding increase in carbonate alkalinity is a measure of the amount of CDR that occurred in the reactor system (e.g., Rau, 2011; Rau and Caldeira, 1999). The error on these measurements is fairly straightforward to ascertain; we will do this on a daily basis with standard reference solutions, including deionized water equilibrated with atmospheric carbon dioxide and a pH buffered solution. Additionally, we are developing software to compile, report, and visualize the realtime and lab-based data generated by our system in the field.

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.)*

The CREW process has limited durability risks with respect to carbon sequestered. The CO2 removed in our reactors will be directly quantified through measurements of the influent and effluent streams (see 4a). However, as noted in 2a and 2b, the extent of carbon re-released over a 10,000 year timescale and beyond (once our effluent stream is discharged to the oceans) will be calculated through an Earth systems model (e.g., Ridgewell and Zeebe, 2005; Adloff et al., 2021). This cGENIE model directly tracks the carbonic acid system and the extent of carbonate precipitation, using the difference between a baseline run and multiple scenarios with different magnitudes of alkalinity discharge from CREW deployments.

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.
Mineral weathering	For our containerized enhanced weathering process, the uncertainty is low (1-5%) as we are monitoring in situ CO2 removal and thus weathering rates (see 1a).
Alkalinity loss	Uncertainty for alkalinity loss in our process is medium (5-20%). If the effluent from our system is discharged with a pH less than 6.5, there may be loss of CO2 that was converted to bicarbonate during weathering (Zeebe and Wolf Gladrow, 2001).
Secondary mineral formation	Uncertainty is low (1-5%). Because we will be using limestone as the mineral feedstock, there is a minimal likelihood of clay formation. However, the back reaction – carbonate re-precipitation - will be monitored by tracking changes in hardness in our effluent.
Leakage	Uncertainty surrounding leakage after our effluent is discharged is medium (5-20%). At thousand year timescales, some of that bicarbonate will be converted to calcium carbonate—rereleasing CO2 to the atmosphere. This can be tracked using the Earth System model, cGENIE (Ridgewell and Zeebe, 2005; Adloff et al., 2021). Additionally, if the effluent from our system is discharged with a pH less than 6.5, there

	may be loss of CO2 that was converted to bicarbonate during weathering (Zeebe and Wolf Gladrow, 2001). However, if the CO2 stored with our process is discharged directly to large waterways or marine settings, this uncertainty will be minimized.
Materials	The uncertainty surrounding the impact of material sourcing in our process is low (1-5%) and well constrained (see LCA).
Energy	The uncertainty surrounding the impact of energy use in our process is low (1-5%) and well constrained (see LCA).
DIC residence time	Similar to other EW projects, DIC residence time will have a low uncertainty (1-5%). For our project, the bicarbonate generated by our system will be directly discharged into the ocean after passing through our partner site's wastewater system. With decades of sampling and modeling, there is consensus that the residence time of bicarbonate in the oceans is on the order of 10,000 years or greater (e.g., 88-121 kyr Middelburg et al., 2020; 100-1,000 kyr Renforth and Henderson, 2017), which is effectively permanent from a human time scale. However, over a >10,000 year interval some of that bicarbonate will be converted to calcium carbonate—rereleasing CO2 to the atmosphere. We will track the extent of carbon lost—if any—during this discharge using a Earth system model (cGENIE; Ridgewell and Zeebe, 2005; Adloff et al., 2021) that allows for modeling of a point discharge of carbonate alkalinity.

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?

> Model runs predict a maximum extent of carbon leakage with 16-22% of CO2 captured during EW with carbonates lost from the oceans over 100-year timescale, depending on the exact emissions scenario. With high emissions scenarios (RCP 8.5), less CO2 is lost from the oceans with a given carbonate alkalinity injection.

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.?

> We have developed a hardware and software package to monitor, compile, report, and visualize CO2 fluxes in our lab-scale containerized weathering system, which will be used for our field-deployed project and future deployments. However, this project will be the first time we are deploying our method in the field. Therefore, the interplay between sensors, controls systems, and software will likely

need optimization as we expand from our first deployment to commercial scale. Additionally, there is uncertainty on the durability of the sensors under field conditions, and we will need to test their general lifespan as well as calibration frequency when operating daily in the field. In sum, this project will be an essential step in demonstrating that containerized enhanced weathering can lead to quantifiable CDR. This project will generate data that will allow us to test the assumption that we can move from lab experiments to field scale deployments.

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)?

We are pleased that multiple organizations (Puro.Earth and Verra among others) are pursuing protocols for verifying enhanced weathering credits; members of our team are working with these organizations on these efforts. We are confident that our process and protocols would be a prime candidate for early credit registration with a certification partner. However, our initial goals are to demonstrate that containerized enhanced weathering is viable at scale and show that we can track carbon fluxes with very high attribution confidence. Therefore, our immediate plan is to propose our own protocol that rigorously outlines 1) the best method of tracking CDR in our system via in situ monitoring and sampling and 2) how to track carbon as it moves from our effluent stream into marine settings, which will be informed by a co-deployed sampling study and numerical modeling at small and large scales (e.g., with regional ocean models and earth systems models, respectively).

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).

$810 /ton CO2

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

Component	Levelized price of net CDR for this project ($/tonne)
Capex	207 $/tCO2

Opex (excluding measurement)	Fixed OPEX = 374 $/tCO2 Variable OPEX = 67 $/tCO2
Quantification of net removal (field measurements, modeling, etc.)[2]	Sensor cost is included in Capex above. Quantification occurs via in situ monitoring, therefore we report here the cost of all sensors for the project = $90,244
Third party verification and registry fees (if applicable)	-
Total	Total = 647 $/tCO2 * 20.2% margin = 810 $/tCO2

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?
Feedstock	$15-40 per ton	$12	Through discussions with mining and grinding experts, it is likely that during commercial optimization we would be able to easily source widely available limestone, mine, and grind for a total cost of ~$12 per ton. For example, Beerling et al., 2020 estimate the cost of mining material at ~$7/t. We estimate less than $1/t is required to grind limestone to 500 microns (from grinding energy model fit Strefler et al., 2018 and assuming $0.13/kwh). By sourcing feedstock from <100 km, this would lead to a total cost of ~$12/t for mining, grinding, and transportation depending on mode of transport.
Labor	One employee at $80,000 per year is responsible for operation and	5 employees at $80,000 per year are responsible for operation and maintenance of	We compare our estimate with other industries that involve field-deployed hardware, such as the drilling crews in the oil and gas industry, where typical crews are a 5-person team. Given that

[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.

	for small-scale unit.	deployment of 10 large scale units.	our envisioned NOAK system (i.e., a series of 10 modular reactors built in shipping containers) is simple to operate relative to a drill rig, we estimate that we would need 5 employees to operate and maintain our NOAK system.

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

> Cost of CAPEX at FOAK and NOAK scale is currently uncertain because we are still in the design phase and total cost is in flux. However, our initial designs are simple and learnings from the wastewater, oil & gas, and chemical industries provide us with important points of comparison. We are bringing in engineering expertise to aid in the design of the CREW system at FOAK and NOAK scales.

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.).

> The costs in the TEA spreadsheet are comparable: $68/t CO2 captured as predicted by our own models and $69-72/t CO2 as predicted by Frontier's TEA sheet.

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.)

> Inclusion in 45Q would be transformative for carbon removal and storage, as well as for enabling a storage-based business model. It would expand our ability to support the CDR industry, decreasing the industry's reliance upon underground injection as a means of CO2 storage.

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.

> We conducted an initial strategic stakeholder mapping and analysis, which was reviewed by the project team and advisors. Important stakeholders for the pilot include:
> - Yale CCL team (New Haven)
> - Financial donors supporting the project, including Grantham Foundation and others (USA)
> - Partner site operators and board members (New Haven)
> - Connecticut Department of Energy and Environmental Protection (CTDEEP) - state government permitting and regulatory authority (Connecticut)
> - Yale University - many departments including Yale Ventures (New Haven)
> - Suppliers, including minerals, equipment, and service providers (USA)
> - Carbon offset buyers, project developers, verifiers, and registries (global)
> - Local community (New Haven)

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.*

> Work was conducted in-house and with support from the Yale CCL.
>
> Operational: We have engaged with CTDEEP to gain an approval letter for the project, indicating that the facility's discharge permit will not be affected. Work was supported by the Yale CCL and Murtha Cullina, CT-based environmental law firm. We also engaged with Yale Facilities, Office of Risk, Office of General Counsel, Yale Ventures (on IP), and Government Affairs for this project. We engaged with municipal wastewater facility operational staff, leadership and board via email, onsite meetings, and presentations to allow for the installation of the pilot.
>
> Supplier and Commercialization: We engaged with USGS to allow for the donation of the initial pilot tanks. We interviewed offsets buyers. We engaged with suppliers by visiting mines, meeting over zoom, and communicating via email. We have also communicated with scientists in departments of natural resources across several states to learn about regional mining and quarrying practices. We have discussed environmental impact and considerations with leading environmental NGOs such as RMI and EDF. We spoke with several early-stage equity investors to gauge interest in supporting commercialization. We have engaged with several DAC companies about offering storage solutions. We are about to engage with the IRS to seek a response to 45Q qualification. We are about to engage with the DOE's DAC Hub program.
>
> Environmental Justice: We will discuss more details about engaging with local communities impacted by operations in the EJ section.

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?

> We have learned that permitting and approvals will be state-based and require a thoughtful approach, that working closely with governments and local stakeholders will be key to understand and monitor

environmental impacts, and that coordinating closely with project sites will help reduce the burden on local communities.

From our various conversations, we have also gained longer-term insights:
long lead-times should be expected for equipment design and manufacturing; prices for delivered minerals depend on the economic environment; logistics of transporting materials and equipment require close attention to minimize operational and local interference; local environmental impacts need to be proven.

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?

For our project site in New Haven, we are leveraging strong relationships between Yale, the facility, and the city of New Haven to ensure successful stakeholder relationships.

We intend to develop and implement site-specific engagement plans for deployment and feedstock locations. We have significant in-house experience with similar stakeholder engagement strategies and communications. Local engagement with community members close to feedstock mines and project facilities will be very important, especially if there is significant increase in traffic, material dust, and general disturbance to daily life.

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.

We have conducted an initial EJ review and analysis using Justice40 and EPA EJ GIS maps and policies. For our longer-term deployment, moving large volumes of rock to sites may require last-mile trucking, contributing to worsening air quality and particulate matter levels along the transportation routes. These routes may go through communities identified as having EJ concerns, especially in urban areas. Several co-benefits of our project can be directed towards identified environmental justice communities. For example, job creation (such as onsite management, field technicians, mechanics, transportation, and materials handling jobs) in these economically marginalized regions will help to generate meaningful economic benefits. Co-benefits of ocean alkalinity enhancement may help climate-affected communities including shellfish farmers and laborers.

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

[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

We have conducted an initial environmental justice analysis using screening tools (i.e. EPA EJSCREEN) to identify existing EJ burdens and concerns for communities in the region of interest. We intend to perform a more formal EJ data analysis in consultation with community stakeholders to identify additional environmental burdens and opportunities for investment in New Haven, and for additional expansion sites. We also plan to optimize transportation modes and routes to minimize negative impacts on identified environmental justice communities and maximize local economic gain. The positive economic benefits generated from our project will be directed to these communities to the greatest extent possible. Additionally, implementing this project for wastewater facilities will improve operations and therefore enhance environmental treatment and increase economic performance. Meaningful engagement of marginalized populations in the community will be a key component of community-level planning processes as well.

8. Legal and Regulatory Compliance

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

For our project deployment, we reviewed permits with facility managers to ensure we are staying within the scope of existing issued permits. This was confirmed by CTDEEP in writing and permission was granted to proceed with the project.

For longer term projects, we have sought advice on environmental permitting and approvals needed in Connecticut, Washington and Oregon. We have engaged legal counsel on 45Q applicability, patent drafting and licensing agreements, and incorporation.

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.

For the project, we have the needed permitting through our facility partner.

Longer term, if partnering with existing facilities, we will need to confirm the system application is within limits of existing permitted water intake and discharges. If we operate as a separate facility, we will need our own intake and discharge water permitting; we have identified the filing process for these permits. Local land-use and building approvals by states and municipalities may be needed. For example, in Washington state SEPA may apply, requiring an Environmental Review. Air quality permits may be needed to transport mined feedstock (currently under review).

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?

No

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.

> No remaining uncertainties for the current project.
>
> For future project sites and applications there are remaining uncertainties around regulations within states beyond those reviewed, needed compliance for international projects sites, and criteria for the application of 45Q.

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.

> No

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))*	150 tons
Delivery window *(at what point should Frontier consider your contract complete? Should match 1(f))*	December 2023
Levelized Price ($/metric tonne CO_2) *(This is the price per tonne of your offer to us for the tonnage described above)*	$810/ton of CO2

Application Supplement: Surface Mineralization and/or Enhanced Weathering

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

Source Material and Physical Footprint

1. What source material are you using, and how do you procure it?

We will be using limestone as the feedstock for this project. It will be procured from established limestone quarries in the vicinity of the project site (relationships and pricing in progress). We will continue testing samples of limestone from a range of quarries across the U.S. to understand feedstock sourcing for future projects.

2. Describe the ecological impacts of obtaining your source material. Is there an existing industry that co-produces the minerals required?

There is a relatively substantial ecological impact from limestone mining and milling activities, including but not limited to: potential changes to aquifer regimes, fugitive dust generation, and habitat destruction (Ganapathi & Phukan, 2020). However, there is an existing industry that produces this mineral feedstock (6.59 Gt/year), with approximately 959 Mt/year produced in the U.S. alone (Caserini et al., 2022). For this project, we will procure the necessary materials as product from our suppliers. We are investigating fine limestone waste material (e.g. 300,000 ton/year at one limestone quarry of interest) and recycled concrete waste material as potential feedstocks in the future.

3. Do you process that source mineral in any way (e.g., grinding to increase surface area)? What inputs does this processing require (e.g. water, energy)? You should have already included their associated carbon intensities in your LCA in Section 3.

Enhanced weathering as a means of CDR operates partially by increasing the reactive surface area of rocks by milling the rocks to a powder. Therefore, processing our source material will require energy to grind before the feedstock can be used. Grinding energy is an input to our LCA. In the long term, we will consider whether milling should be done as a wet or dry process; wet grinding is more efficient but comes with extra cost and higher emissions for drying and/or transport of wet material.

For this project, we are not processing any feedstock directly, as this will be done by suppliers. However, we are still including it in our LCA for a full view of our impacts.

4. Please fill out the table below regarding your project's physical footprint. If you don't know (e.g. you procure your source material from a mining company who doesn't communicate their physical footprint), indicate that in the table below.

	Land area (km^2) in 2021	**Competing/existing project area use (if applicable)**
Source material mining	Unknown	As the existing infrastructure for limestone mining is vast, we do not expect a measurable increase in the amount of surface mining in the U.S.
Source material processing	Unknown	As above, the existing infrastructure for limestone mining and milling is vast. Therefore, we do not expect a measurable increase in the land area required to supply the necessary feedstock for our pilot.

Deployment	6,000 sq ft	The CREW system will have a footprint of ~640 square ft. This is the size of the skid and an equivalent space to have tanks to load feedstock. The deployment of the physical system will fit within existing infrastructure at our partner site. The land area required for feedstock storage, as well as the containerized system, will be <6,000 square ft. The alternative use of this area is a parking lot and other paved open space.

5. How much CDR is feasible globally per year using this approach? Please include a reference to support this potential capacity.

> With just capturing CO2 from the US waste organic sludge incineration process, the CDR capacity is ~3-4 million tons of CO2. This assumes that 13.8 million tons of dry sludge are collected annually (Seiple et al., 2017), of which ~15% is incinerated (Seiple et al., 2017). The organic carbon content of dry sludge is ~40-50 wt % therefore:
> 13.8 million t dry sludge x 15% incinerated x 45% wt C x 3.67 t CO2/t C = 3.4 million tCO2.
> Additionally, there are ~200 million metric tons of CO2 of estimated capture from EU waste incineration (Rosa, Sanchez, Mazzotti, 2021).

6. If you weren't proceeding with this project, what's the alternative use(s) of your source material? What factors would determine this outcome?

> Limestone is used as an aggregate, a component of cement concrete, a feedstock for lime production, a raw material for glass and metal-processing industries, a soil conditioner, and more; usage is determined by regional demand. Our project will use a pulverized limestone sold for soil conditioning, termed agricultural limestone.

Human and Ecosystem Impacts, Toxicity Risk

7. What are the estimated environmental release rates of heavy metals (e.g. Cr, Ni, Pb, Hg)? Dust aerosol hazards? P loading to streams? How will this be monitored?

> The release of heavy metals from limestone is near zero, as confirmed in the lab. All incoming feedstock will be analyzed using standard tools before being used in the field.
>
> Our larger-grained feedstock will be delivered in bags to limit dust. Dust monitors can be deployed as needed.

8. If minerals are deployed on croplands, what are the estimated effects on crop yields? Include citations to support this claim. How will actual effects be monitored?

N/A

9. How will you monitor potential impacts on organisms in your deployment environment? (e.g. health of humans working in agricultural contexts, health of intertidal species, etc.)

The key environmental risk is the accumulation of alkalinity in nearshore environments. We continuously monitor the effluent of our system. The project risk is extremely low given project scale. We will be: 1) developing a regional particle dispersion model to predict areas of alkalinity accumulation in the local area; and 2) collecting water, soil, and plant samples regularly. When scaled, the risk is less clear. We plan to conduct experiments with fauna of interest where we measure the effects of a range of alkalinities on several response factors, including survivorship, growth rate, and fecundity.