⁘ Frontier

Aquarry

Carbon dioxide removal prepurchase application

Summer 2024

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](https://github.com/frontierclimate) after the conclusion of the 2024 summer purchase cycle. Include as much detail as possible but omit sensitive and proprietary information.

Company or organization name

Aquarry, Inc.

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

HQ: Emeryville, CA; technical team: Denver, CO

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

Kate Murphy and Spencer Whitman

Brief company or organization description <20 words

Aquarry converts flooded surface mines—"pit lakes"—into massive, permanent carbon sinks.

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 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. 1000-1500 words

Aquarry is a US public benefit corporation working to convert abandoned mine sites for CDR, achieving permanent, gigaton scale, measureable carbon removal without high usage of land or energy. We address both excess atmospheric CO_2 and historical mining contamination through a single solution which we call **pit lake alkalinity enhancement (PLAE)**.

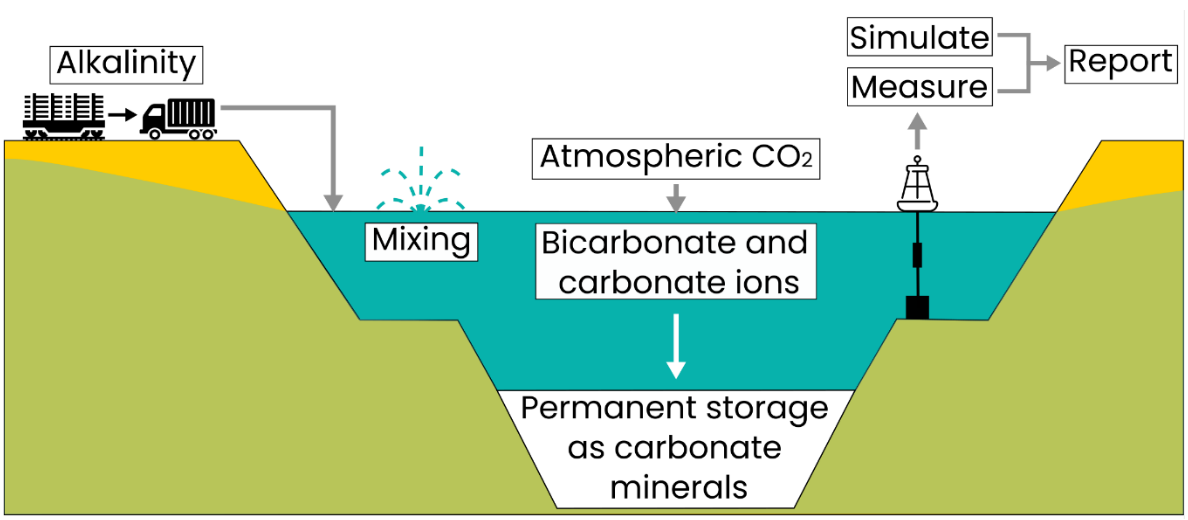
[1] We use "project" throughout this template, but the term is not intended to denote a single facility. The "project" being proposed to Frontier could include multiple facilities/locations or potentially all the CDR activities of your company.

Pit lakes are water bodies that form after the closure of mine pits which intersect the water table. During mine operation, these pits are actively pumped dry; when operations cease, they flood with surface and groundwater. Surface mines and their resulting pit lakes are widespread, with thousands of sites globally on every continent save Antarctica. They often feature poor water quality and physical hazards such as unstable walls, making them both financial and environmental liabilities. Prior to adoption of stricter regulations in the 1970s, many mine sites (including pit lakes) were left untreated, and many contaminated and hazardous sites remain today.

PLAE is similar to ocean alkalinity enhancement (OAE) in that we add alkaline materials, increasing pH and thus converting aqueous CO_2 to bicarbonate and carbonate ions. This depletes the water of CO_2 with respect to the atmosphere. CO_2 is then drawn down into the water according to Henry's law until equilibrium with the air is re-established. *Unlike* OAE, our primary storage mechanism is as **stable carbonate minerals** rather than as bicarbonate. Since pit lakes are relatively contained water bodies with chemistry distinct from the ocean, we are able to intentionally drive the concentrations of dissolved carbon and alkaline metals far above saturation such that carbonate minerals like calcite (CaCO3) form and sink to the bottom of the lake, while a small portion of total carbon remains as bicarbonate or carbonate ions. This leads to **facile measurement**: dissolved carbon concentrations can be readily measured using in situ sensors or laboratory titrations, and precipitated carbonates can be sampled from the lakebed and analyzed in a lab using well-established methodologies.

Formation of carbonates enables **high areal density of storage per site**. CO_2 capacity is a function of the bulk density and thickness of carbonaceous sediment in the lake. Pit lakes are frequently 10s to 100s of meters deep and can contain billions—sometimes 100s of billions—of liters of water. Storage capacity can then exceed 100 Mt CO_2 in some of the largest lakes. This storage is also permanent, since mineralization is one of the most stable CO_2 storage mechanisms known. With thousands of sites globally, we estimate total capacity using our method could exceed **100 GtCO$_2$**.

Implementation: Aquarry's process is depicted in the diagram below. First, potential sites are analyzed and modeled to determine suitability. Factors determining suitability include hydrology, water and ore body chemistry, water volume, proximity of alkalinity, and pre-existing infrastructure such as a nearby rail spur. We then source alkaline materials available on or near the mine site. These materials may comprise alkaline wastes such as steel slag, coal ash, mine tailings, or cement kiln dust, or newly-mined ultramafic rocks. Selection of feedstocks is based on reactivity, cost, location, and mineralization capacity. Materials are transported to the site (if not already present) and incrementally mixed with water to increase pH. Fountains or aerators are used as needed to speed absorption of CO_2, which speciates to carbonate and bicarbonate. As concentrations of Ca^{2+} or Mg^{2+} and CO_3^{2-} increase, carbonate minerals will passively form and settle to the lakebed. This represents a permanent means of storage as a carbonate sediment.



The process is monitored via in situ sensors which track parameters such as pH, pCO_2, oxidation-reduction potential (ORP), dissolved oxygen, and specific conductivity. These real-time data are used to inform our models and process before adding the next dose of alkalinity. Additionally, we periodically collect samples of water and sediments for laboratory analysis. Results of these analyses are used to quantify carbon removed, optimize the process, and in reports to regulators.

Differentiation: Aquarry is the first group to propose the use of pit lake alkalization for CDR—no academics, companies, or other organizations are in the space. No other companies are using pit lakes for CDR by any means. Further, PLAE is distinct from other CDR technologies in blending the best aspects of OAE and ERW. Like OAE, we alkalize water bodies to induce CO_2 absorption from the atmosphere, but we do so in a manner that is far less environmentally risky and far more easily measured since we do not suffer from the extreme dilution which occurs in the ocean. As in ERW, we source alkalinity from silicate minerals or industrial wastes and store CO_2 as durable carbonate minerals. However, as opposed to ex situ ERW we require no reactors, high temperatures, or concentrated CO_2, keeping capex and energy costs low. We also avoid the downsides of surficial ERW, which requires large areas of land and faces measurement challenges due to runoff.

The ideal CDR technology can store gigatons of carbon for thousands of years, costs <$100/tCO_2$, uses little energy, is measurable, has co-benefits, and minimizes use of high-value land. All existing technologies have tradeoffs, e.g., reforestation is low cost and has co-benefits, but is not durable or easy to measure. Ours is the only solution which meets or exceeds all these criteria: we can capture and permanently store gigatons of CO_2 for <$100/t, with facile measurement, low energy requirements, while utilizing degraded land and cleaning up toxic mine sites. While the planet needs an "all of the above" approach to stabilize the climate, our technology is unique in its potential to provide CDR of the highest value at a low cost.

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 cost and scale criteria?[2] What is your approach to quantifying the carbon removed? Please include figures and system schematics and be specific, but concise. 1000-1500 words

Aquarry is building the world's first demonstration of carbon removal via alkalization of a mine pit lake. For this proof of concept project we will use a relatively small lake with total capacity in the 10s of $ktCO_2$, validating our capture rate and storage capacity projections at a meaningful scale. Additionally, we intend to use chemically pure feedstocks such as low-carbon lime to demonstrate the safety and efficacy of our overall process decoupled from safety concerns associated with alkaline wastes, which are our long term expected feedstocks. Building trust with pit lake owners is paramount, so this approach of "un-stacking" risk will facilitate future development of our technology.

Costs: The largest costs associated with this project are in purchasing and shipping chemically pure feedstocks ($408/tCO_2$). As we begin using less processed, nearby feedstocks such as steel slag our costs will come down consierably. For our solution to achieve $100/t, the following need to happen:

1. We must reduce feedstock prices by sourcing reactive alkaline wastes and addressing stakeholders' concerns about contamination. Additionally, these wastes must be available within a short transportation distance of a pit lake and can preferably be transported via rail.
2. We must operate in larger lakes. Setup and capital costs do not scale linearly with lake volume, which determines capacity. Many lakes have projected capacity >10 $MtCO_2$, which drastically lowers per-ton costs as compared with the current project, with capacity <100 $ktCO_2$.

[2] We're looking for approaches that can reach climate-relevant scale (about 0.5 Gt CDR/year at $100/ton). We will consider approaches that don't quite meet this bar if they perform well against our other criteria, can enable the removal of hundreds of millions of tons, are otherwise compelling enough to be part of the global portfolio of climate solutions.

Scale: For this project we are targeting a lake with capacity approximately 50 ktCO_2 when 10% of the original water volume has been filled with precipitated carbonate sediment, i.e., a lake with volume approximately 1M m^3. Assuming a project lifetime of 10 years, we will remove 5 ktCO_2/yr (gross). For the much larger lakes we plan to work with in the future, we assume an average volume of 120M m^3 (average of the top 50% of lakes in our internal database) and that we fill to 50% of the original water volume, yielding average capacity 28 MtCO_2 per lake. If each lake has a 25 year lifetime (i.e., we capture on average 1.12 MtCO_2/year/lake), we can achieve 500 Mt/yr by working in 446 pit lakes. This is a reasonable number considering there are likely tens of thousands of lakes globally (of all sizes).

Quantification: Carbon removed is measured by determining carbon content and thickness of sediments via periodic sampling and laboratory analysis via combustion and/or acid digestion. We additionally measure dissolved carbon in the water via in situ pH and pCO_2 sensors, with periodic validation via laboratory measurements of water samples. These measurements are direct and not heavily reliant on models except in interpolating between discreet measurement locations.

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. 500-1000 words

The biggest risks we've identified are:

1. Variable CO_2 transfer rate between the atmosphere and the lake water. CO_2 is driven into water according to Henry's law due to disequilibrium between atmospheric and dissolved (aqueous) CO_2. The transfer rate depends on concentration difference, surface area, and environmental factors. Through excess alkalinity addition we can achieve high atmosphere-solution concentration gradients, which will speed transfer. We also speed transfer by artificially increasing surface area using fountains, sprayers, or aerators. However, we have no control over rain, wind, and temperature, which will substantially affect the transfer rate. To mitigate this risk, we design for a "worst case" scenario in which there is little rain or wind and substantial winter freezing, ramping above our baseline when environmental conditions are the most favorable.

2. Environmental hazards. While pit lakes are relatively closed systems, they may have some amount of discharge to groundwater or surface waters. Potential sources of contaminants include our alkaline feedstock or the host orebody itself, if particular species become mobilized during treatment. We can largely mitigate these risks by careful selection of the site and alkaline materials combined with thorough sampling and modeling before commencing treatment. Once water treatment has begun we will regularly sample water from multiple locations within the lake and analyze for contaminants of concern. Additionally, the use of finely ground materials and activity around an unvegetated mine site may lead to increased dust. To address this, we will implement dust suppression techniques commonly used on mine sites.

3. Finding pit lake owners willing to partner on pilot and first of a kind projects. The mining sector and their regulators are rightfully conservative with respect to water quality and safety, and we are taking steps to build trust. This has meant early discussions with regulators and site managers about their potential concerns and designing our R&D program to address them. Our strategy to scale gradually from benchtop to intermediate scale "mesocosm" experiments to small lakes has resonated with site owners as a means of minimizing risk. Once we've demonstrated safety in initial sites we expect acquisition will be substantially easier.

4. The diversity and complexity of water quality regulations, which vary between states, provinces, and countries. Navigating the numerous regulatory agencies as we expand operations may present a significant challenge. Furthermore, while we expect to maintain or improve existing water quality, our process represents a departure from standard mine water treatment and

beneficial uses of pit lakes are generally not recognized. To mitigate these risks, we will engage with consulting firms which work on mine remediation across different geographies.

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)*	18,870
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	Q4 2027
Levelized cost ($/ton CO_2) *(This is the cost per ton for the project tonnage described above, and should match 6d)*	$788 (this will be substantially lower at scale)
Levelized price ($/ton CO_2)[3] *(This is the price per ton of your offer to us for the tonnage described above)*	$900

[3] This does not need to exactly match the cost calculated for "This Project" in the TEA spreadsheet (e.g., it's expected to include a margin and reflect reductions from co-product revenue if applicable).