pHathom Technologies Inc.

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 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

pHathom Technologies Inc.

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

New Brunswick, Canada

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

Kimberly Gilbert, Andrew Ray

Brief company or organization description <20 words

We are working to make thermal power production carbon negative by harnessing the ocean's natural carbon cycle.

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

pHathom's technology enables the capture and long-term storage of biogenic CO_2 through a novel approach that captures CO_2 from biomass combustion using limestone and other alkaline minerals, and then stores the CO_2 by harnessing the ocean's natural carbon cycle. This unique approach enables low-cost bioenergy CCS (BECCS) in coastal locations that do not have ready access to

[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.

suitable geologic storage for CO_2. pHathom's technology, if successful, has the potential to rapidly scale into a GT/yr CDR credit generation opportunity.

The specific project that is proposed for this application will generate approximately 500 tons of net CDR credits through the application of the technology at a pilot at a power plant in New Brunswick, Canada. This pilot will leverage existing equipment at the plant, including the flue gas desulphurization (FGD) unit, a large auxiliary tank, and the existing wastewater treatment facilities, and its primary purpose is the validation and quantification of the CO_2 captured and ultimately stored as bicarbonate in the ocean. The experimental design of the pilot will address many of the current scale-up risks of the technology.

The following sections describe in more detail the key aspects of pHathom's technology, and how it is integrating a set of core, well-understood technologies into a novel system.

Accelerating a Natural Process

pHathom's techology captures CO_2 from biomass power plants, converts it to bicarbonate using Accelerated Weathering of Limestone (AWL), and stores it in the ocean as bicarbonate, where it will be neutral and stable for tens of thousands of years.

To advance this opportunity we are partnering on 2 fronts:

- On biomass supply, to ensure sustainably sourced biomass for the pilot plant as well for the subsequent commercial deployment we are partnering with Statolith, a sustainable biomass supply chain and forest management company.
- On measurement, reporting and verification (MRV) of CO_2 capture we are partnering with Aquatic Labs, a leading firm in the measurement of ocean carbon.

Our project is applying a novel methodology to a biomass power plant, leveraging existing industrial equipment.

Leveraging Bioenergy Carbon Capture and Storage (BECCS)

Using biomass for energy in place of fossil fuels reduces the amount of net new carbon from entering the carbon cycle. Trees naturally capture CO_2 from the atmosphere as they grow, storing that as carbon (making up 50% of a tree's mass). When those trees die and decompose, the carbon gets released back into the atmosphere. The cycle found in nature continues as that carbon is in turn captured by the next generations of trees.

While wood is both natural and renewable, cutting down trees to burn in power plants could result in accelerating the degradation of our forests if done in an unsustainable manner. However, if the wood is sustainably sourced, there is an opportunity to use AWL to effectively capture and durably store the CO2 removed by the trees as they grow, and generate carbon negative electricity from our existing infrastructure, all while helping to return balance to our planet and oceans. To ensure that the biomass is sustainably sourced, we are partnering with Statolith, a sustainable, supply-chain management company.

Accelerating Weathering of Limestone (AWL)

When rain falls, it absorbs atmospheric CO_2, creating carbonic acid, which dissolves limestone when it lands, neutralizing the acidity and, converting the CO_2 and dissolved limestone (calcium carbonate) into stable bicarbonate ions, which run off into the ocean where they remain for 10,000+ years. This reaction follows the following chemical reactions:

$CO_2 + H_2O \rightarrow H_2CO_3$ Equation 1

$CaCO_3 + H2CO_3 \rightarrow Ca_2+ + 2HCO_3-$ Equation 2

However, so much CO_2 is now being emitted that natural processes can't keep up, which is causing ocean acidification. We accelerate the weathering of limestone (AWL) in an industrial process at a rate equal to the facility emissions by capturing the emissions directly at the stack in a water/limestone slurry contactor, creating bicarbonate-enriched seawater, which is pH adjusted, then returned to the ocean where the stable bicarbonate ions stay dissolved in seawater for thousands of years.

MRV Through Direct Measurement
Because our process is onshore, we can make direct total alkalinity, pH, dissolved inorganic carbon and/or PCO_2 measurements upstream and downstream of our process to calculate how much CO_2 is captured, neutralized, converted to bicarbonate and stored. In addition, we will establish a mesh network of deployed sensors in the bay where the outflow occurs to detect residence time, bicarbonate buildup and potential calcium carbonate precipitation, which would indicate outgassing.

Using these long-term, distributed measurement methods, we not only measure how much CO_2 gets converted to bicarbonate and stored in the water, but also gain assurances of its durability. Because the highest likelihood of precipitation/off-gassing happens where the concentration is highest, measuring close to shore gives us the greatest confidence of success.

We believe that for CDR to scale in a trustworthy manner, MRV should be performed by an independent party that does not benefit from the measured amount of CO_2 sequestered. In this effort, we are partnering with Aquatic Labs. They are developing scalable marine carbon system sensors that reduce dissolved inorganic carbon measurement uncertainties by ~10x through first of a kind continuous direct total alkalinity sensors. They will assist in the monitoring operations and maintain an independent monitoring record through their Ocean Data Platform that manages all monitoring data from raw signals to quality-controlled outputs in a single platform with easy traceability of every data point. Aquatic Labs sensors capitalize on existing scaled manufacturing techniques, enabling MRV to scale with inexpensive hardware.

Leveraging existing assets
To reduce costs and scale quickly, we use common equipment and processes from the energy and water treatment industries to capture CO_2. Where available we leverage existing systems, such as existing thermal power plants (converted to biomass if they aren't already), their material-handling equipment (e.g. disused coal conveyors), flue-gas desulfurization units, and effluent and once-through cooling water infrastructure.

In addition, our TEA and business plans are written for the base case, which uses limestone as the alkalinity source because it is ubiquitous, and used at large scale in the cement industry, making large quantities (relatively) easily sourced. However, we are also investigating and intend to use other alkalinity sources where possible, including:

- Spent lime from cold water softening at industrial and municipal water treatment facilities. This is high pH waste material (pH 9-10) that is 90% calcium carbonate particulates at around 10 microns. This reduces the need for mining and grinding new limestone and increases the alkalinity potential due to the high pH.
- Steel slag from steel processing can be up to 50% calcium oxide, which is a very strong alkalinity source. While in the US and Canada, there are a couple million tons per year produced, almost 60% of the production is in China and Japan. 10-22 GT of CO_2 per year could be sequestered if all global steel slag was used for ocean CDR[2].
- Mine tailings from certain mining operations (for example nickel mining) that have high concentrations of magnesium oxide, including serpentine, olivine and brucite minerals.[3]

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[2] Moras, C. A., et al. (2024). "Carbon dioxide removal efficiency of iron and steel slag in seawater via ocean alkalinity enhancement." Frontiers in Climate 6.

[3] Canada Nickel Demonstrates Carbon Sequestration Potential of Tailings from the Crawford Nickel Sulphide Project https://canadanickel.com/wp-content/uploads/2021/11/2021-11-10-Canada-Nickel-NetZero-Carbon-Sequestration-News-Release-v10-FINAL-1.pdf

Massive Scale Up Potential
In its sixth assessment report[4] the IPCC outlined both the need and potential for massively scaling up BECCS in order to meet Net Zero Emissions by 2050. Per that report, "The level of CCS and CDR is expected to change depending on the extent of mitigation, but there remains extensive use of both CDR and CCS in scenarios. **CDR is dominated by bioenergy with CCS (BECCS) and sequestration on land,** with relatively few scenarios using direct air capture with carbon storage (DACCS) and even less with enhanced weathering (EW) and other technologies"

This IPCC data shows that in the median scenario 240 billion cumulative tons (or more) of BECCS would be required. While the pHathom technology won't be able to deliver all of that, given its restriction to coastal locations, using the ratio of coastal fossil power to total fossil power (about 25%), coastal BECCS would likely need to remove 60 billion tons of CO_2 by 2050 to reach Net Zero emissions.

Leveraging existing infrastructure can get us there more quicky. In Asia Pacific and the developing world, most of the electricity comes from relatively new coal plants, with an average of 35 years of useful life remaining. Just the coastal coal plants in Asia Pacific, if unabated, will emit an estimated 84 billion tons of CO_2 over their remaining lifetimes and be responsible for an estimated 0.4°C of warming. Converting existing coal plants to BECCS would simultaneously remove coal emissions, replace the energy they produce with a carbon negative alternative, and get the full use out of the trillions of dollars of investments in energy infrastructure that have been made in emerging markets and developing economies.[5]

One of the significant challenges of delivering all of that BECCS will be finding suitable storage located near the biomass and bio-energy plants. This is a particular challenge in Asia–Pacific where many major industrial point emitters do not have access to suitable subsurface geology for CO_2 storage. With combined annual CO_2 emissions of 840 million tons, Japan, Korea, Taiwan, and Singapore in particular face this challenge.

Japan, for example, is a very large market where BECCS can make a significant impact. Japan's coal plants emit 400MT CO_2/year, with most of that on the ocean, where deep sea access enables limestone delivery by cargo ship. With massive limestone outcrops in neighboring nations (Vietnam and Thailand) and massive steel slag waste piles in China, the required resources exist in the region to capture, neutralize and store that CO_2. While many of their plants are coal fired, Japan is actively looking for more carbon neutral or negative solutions.

We are working with consultants and meeting with major industrial players in Japan to understand the potential of introducing our BECCS solution there. Currently, there are currently 586 biomass plants with a total of 4.1 GW capacity in the country, that generate a total of 23.7 TWh of power. If captured, this would result in approximately 25 MT/yr of BECCS potential. In addition, another 4.2 GW of capacity approved)[6], potentially doubling the total capturable CO_2 from existing and approved plants.

Advantages over competing technologies
Other Bioenergy with Carbon Capture and Storage (BECCS) methods typically use amine-based CO_2 capture. While this is a proven capture technology, it is expensive and energy intensive for the following reasons:

- After the CO_2 is captured, the amine sorbent must be regenerated, which requires a significant amount of energy in the form of steam.

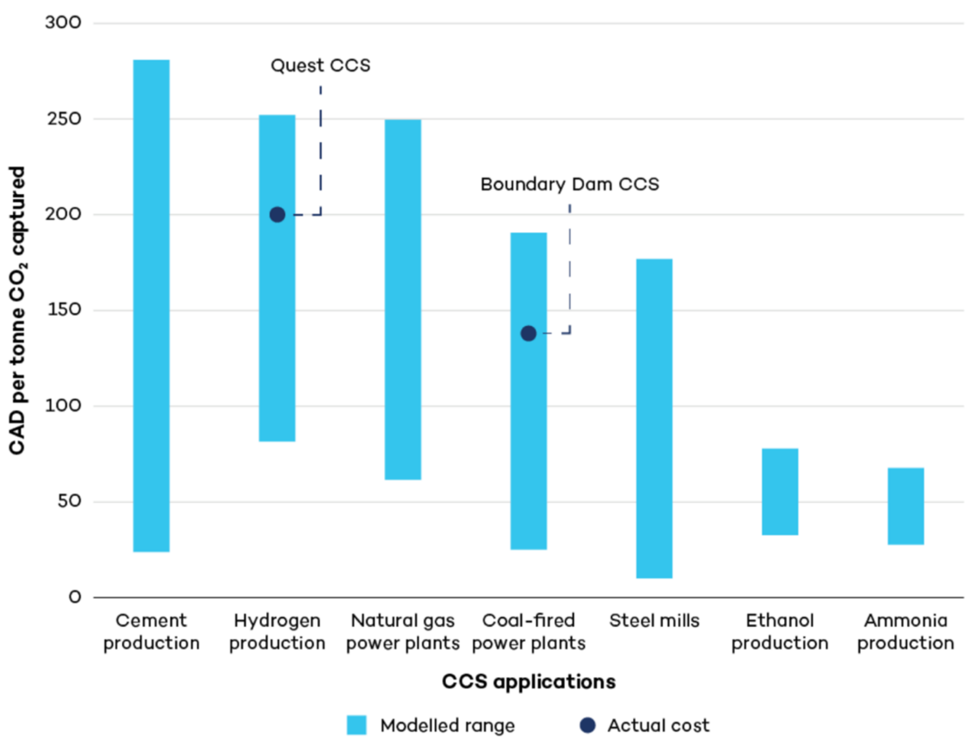
[4] IPCC, 2023. https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter03.pdf
[5] IEA, 2023. https://www.iea.org/reports/coal-in-net-zero-transitions/executive-summary
[6] Japan biomass annual 2023, US Dept of Agriculture https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Japan%20Biomass%20Annual%202023_Tokyo_Japan_JA2023-0071.pdf

- The CO_2 must be compressed for transport, which is a significant electricity draw, resulting in the power plant being de-rated (i.e. producing less power than without power) by 15-20%.
- Pipelines must be built to transport CO_2 to a disposal well, which are expensive ($2-3MM/mile), and can pose significant safety, permitting and regulatory risks
- Disposal wells must be drilled, requiring the full characterization of the subsurface for any site not already used for extensive oil or natural gas exploration
- In many places in the world there isn't suitable geology for sequestration (i.e. Japan) resulting in the CO_2 having to be shipped, or transported by pipeline over very long distances, adding considerably to the cost and reducing net emissions.

The costs of CCS technologies vary significantly depending on the type of capture process employed, the means of CO_2 transportation, and the storage location[7]. Costs also vary depending on the CO_2 concentration[8] in the emissions stream: the lower the CO_2 concentration in the gas, the higher the energy demand required for separating out the CO_2, resulting in higher costs.

The table below provides a breakdown of just the CO_2 capture costs by production source[9]:

Figure: Estimate of carbon capture costs by industry and category of capture technology - 2021 CAD



In contrast, our methods capture, neutralize and store the CO_2 (as bicarbonate) in the ocean without the need to separate the CO_2, regenerate the sorbent, purify and compress the CO_2, saving

[7] Energy Strategy Reviews, 2018. "An Assessment of CCS Costs, Barriers and potential." https://www.sciencedirect.com/science/article/pii/S2211467X18300634?via%3Dihub
[8] Global CCS Institute. Global Status of CCS 2021. https://www.globalccsinstitute.com/wp-content/uploads/2021/10/2021-Global-Status-of-CCS-Report_Global_CCS_Institute.pdf
[9] International Institute for Sustainable Development, 2023. https://www.iisd.org/articles/deep-dive/why-carbon-capture-storage-cost-remains-high

significant cost and energy while also eliminating the need for a dedicated pipeline to transport the CO_2 to a suitable storage site.

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

[10] We're looking for approaches that can reach climate-relevant scale (about 0.5 Gt CDR/year at under $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.

We are building a carbon capture, neutralization and ocean storage system that captures CO_2 from coastal biomass power plants.

Our initial project is for an existing Canadian coal plant testing a switch to biomass that currently emits about 3 MT/yr of CO_2. Under Canadian emissions regulations, that plant must abate CO_2 emissions by 50% by 2030 (and 95% by 2035) or shut down. Due to an existing gap between electricity supply and demand, there is particular interest in finding a solution that doesn't remove firm baseload power from the grid.

Coal contains sulfur, which when burned emits sulfur dioxide (SO_2). In order to capture that acid rain causing gas, most coal plants are fitted with a flue gas desulfurization (FGD) unit, typically consisting of a large limestone scrubber. When testing a fuel switch from coal to wood, since there is no sulfur in wood, the limestone scrubber would not be needed, and would otherwise be bypassed. However, during their 2-week periods of biomass testing, this large limestone scrubber can be re-purposed for use in our AWL process to scrub the biomass flue gas and capture CO_2 instead of SO_2.

While large, the FGD has been optimized to capture small amounts of SO_2 and therefore can't capture and neutralize the full volume of CO_2 in the flue gas. Run as designed for SO_2, it can however capture approximately 10 tons per hour of CO_2 but neutralize only about 1 ton per hour. While this is a low efficiency, it will still allow us to functionally demonstrate the viability of the process at scale (including capture, neutralization, conversion to bicarbonate and ocean storage), while also characterizing key parameters required for system optimization.

Using this $300M piece of existing equipment (along with other existing plant equipment) allows us to significantly reduce the equipment costs for the project. However, as it is unoptimized for our purpose, it comes with higher operating costs, putting our current cost for this project in the range of $944/ton of CO_2 captured, neutralized and stored.

As the project leverages existing equipment to functionally demonstrate the technology, it also validates its core approach of using currently available hardware to build the solution. This not only reduces the cost of development, but also greatly simplifies deployment at scale, as fully developed supply chains (and costing data) already exist for the core components. Although there is potential for new hardware to be developed to further improve the process, it is not required to meet the Frontier cost or scale targets.

A similar approach is taken for sourcing alkalinity, where the baseline case calls for cheap, abundant limestone (5,000 Gt within 10km of the coast[11]) that already has a fully developed supply chain that produces 7Gt per year. This greatly simplifies sourcing limestone at scale. While other sources of waste alkalinity (including limestone fines) could further reduce costs or increase efficiency, they are not required to meet the Frontier cost or scale targets.

Getting the cost below $100/ton will be largely about optimizing the process, rather than developing new technology, while scale will come from using currently available equipment and alkalinity. As proposed, our FOAK deployment consists entirely of components that can be bought (and priced) today, and fully scaled up from bench to the projected scale. It also assumes process improvements and learning rates in line with those achieved by FGDs over their 40-year deployment history.

To quantify CO_2 capture and monitor the bay for storage durability and safety, we are contracting Aquatic Labs as a partner on this initial test. We intend to measure Total Alkalinity (TA), pH, and PCO_2 (although we only require 2 of those to characterize the carbonate system), both upstream and downstream of the carbon capture. In addition, we will measure the same three parameters at three locations in the bay to determine durability. We will also add turbidity to monitor for any calcium carbonate precipitation occurrences, which would be an indication of CO_2 off-gassing.

[11] Casserini et al. (2022). "The Availability of Limestone and Other Raw Materials for Ocean Alkalinity Enhancement"

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

CO_2 capture

The basic process relies on reacting dissolved limestone ($CaCO_3$) with flue gas CO_2, which has generally low kinetics and requires significant mass flows of both water and limestone. In addition, adequate mixing and residence time is required to allow for the formation of bicarbonate ions in the solution.

While all of this has been demonstrated at lab scale, scaling up the technology to operate at T to MT/yr range is a risk and will be a primary focus area.

Ocean Storage

We are relying on ocean storage for the bicarbonate we create through CO_2 neutralization. Our biggest risk is not being able to put it in the ocean. We are mitigating this risk in multiple ways:

Safety Research: We are working with researchers from the Ocean Frontier Institute at Dalhousie University to help identify the levels at which bicarbonate may cause toxicity 1) through chronic exposure and 2) through acute exposure. With this data, we can modify our system so that levels never exceed recommended levels.

Regulatory Process: We are working with federal, provincial and local governments to clearly understand the regulatory pathways for gaining permits to release bicarbonate and verify its safety at the levels in which we are working.

Community Engagement: We have begun conversations and will continue to work with local indigenous communities, fisherman, and the broader community to create an open dialogue and build trust. Our solution must be broadly beneficial or it cannot happen.

Commercialization and Scaleup

Another significant challenge will be developing a commercial-scale integrated solution that an end customer (i.e. a utility operator) would be confident in implementing and operating at an existing or planned biomass plant. Some of the challenges that will need to be overcome include:

Development and validation of commercial scale equipment: We are currently screening potential EPCM partners to help in developing commercial scale equipment that meets the necessary codes, constructability and operability requirements for this type of equipment

Integration with existing facilities: Understanding the required footprint of the additional equipment, along with controls, utilities and other infrastructure will be critical to minimize both capital and operating costs

Training of qualified operators and technicians: It is likely that the skillsets of the operations staff at a typical biomass facility will be inadequate to safely and efficiently operate this type of facility. Developing training and change management tools to effectively equip existing staff, and identifying necessary new staff will be a key part of the commercialization of the technology.

d. **Proposed offer to Frontier:** Please list proposed CDR volume, delivery timeline and price below. If you are selected for a Frontier pre-purchase, 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*	453 tons of CO_2

uncertainty discount proposed in 5c)	(538 x 0.90 – 31)
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	May 31, 2026
Levelized cost ($/ton CO_2) *(This is the cost per ton for the project tonnage described above, and should match 6d)*	$944/ton
Levelized price ($/ton CO_2)[12] *(This is the price per ton of your offer to us for the tonnage described above)*	$1104/ton

[12] 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).