[Lillianah Technologies, Inc.]

Carbon dioxide removal prepurchase application

Summer 2023

General Application

(The General Application applies to everyone; all applicants should complete this)

Public section

The content in this section (answers to questions 1(a) - (d)) will be made public on the Frontier GitHub repository after the conclusion of the 2023 summer purchase cycle. Include as much detail as possible but omit sensitive proprietary information.

Company or organization name

Lillianah Technologies, Inc.

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

Texas, Louisiana, and California

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

Benjamin Slotnick and Michael Beman

Brief company or organization description <20 words

mCDR company using efficient growth and sinking of phytoplankton to remove carbon dioxide from the surface ocean

1. Public summary of proposed project[1] to Frontier

a. **Description of the CDR approach:** Describe how the proposed technology removes CO_2 from the atmosphere, including how the carbon is stored for > 1,000 years. Tell us why your system is best-in-class, and how you're differentiated from any other organization working on a similar approach. If

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

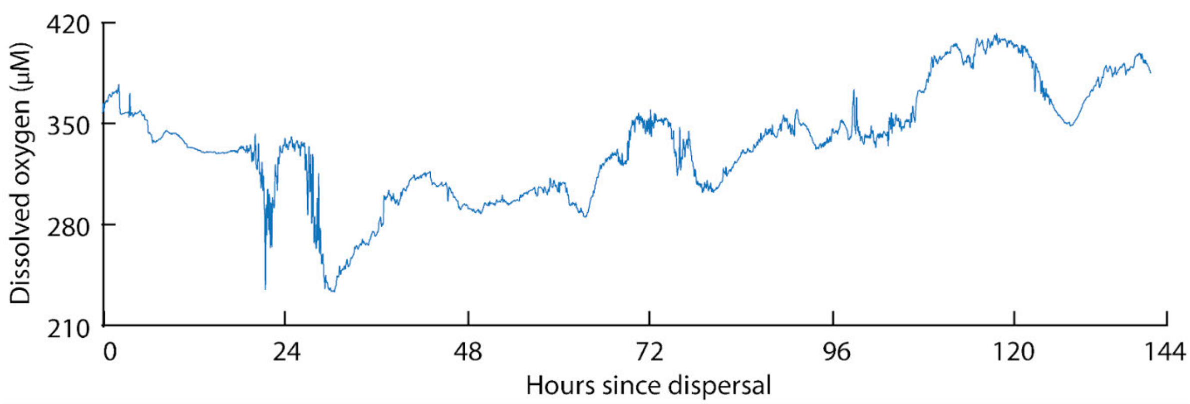
your project addresses any of the priority innovation areas identified in the RFP, tell us how. Please include figures and system schematics and be specific, but concise. Aim for 1000-1500 words.

Our approach removes carbon dioxide (CO_2) from the atmosphere through biomass sinking of phytoplankton in the ocean. Phytoplankton are photosynthetic microorganisms that 'fix' CO_2 during photosynthesis throughout the surface ocean and convert it into different forms of organic carbon; when a significant proportion of this biomass sinks, it effectively removes CO_2 from the surface ocean. As outlined in the pivotal National Academies report on marine CDR, this overall mechanism is one of the best-understood and most cost-effective approaches to mCDR. On a more fundamental level, deposition of phytoplankton remains in marine sediments is what ultimately generated oil and gas reservoirs. We aim to accelerate this by using diatoms that grow their own silica 'shells,' which sinks them and becomes long-term sediment. This is one of several key aspects to our mCDR approach that we believe will maximize speed and efficiency, while we will also advance quantification methods for CO_2 drawdown and directly assess associated ecosystem effects through our MRV. Our approach therefore directly addresses Frontier's ocean-based CDR priority area.

Several unique features boost the overall efficiency of our mCDR approach while also reducing side effects of all kinds—in fact, we expect several co-benefits that we outline throughout our application. The first key aspect of our mCDR approach is that we are targeting human-induced 'dead zones' in nearshore marine environments. Dead zones (aka hypoxic zones) are regions of oxygen-depleted water ultimately caused by excess nutrient runoff from upstream human activities (primarily from agricultural fertilizers and wastewater). Nutrient-rich runoff results in blooms of potentially harmful phytoplankton whose death and decay leads to oxygen consumption. Dead zones can cause fish, crab, and oyster kills, and can also release harmful greenhouse gasses to the atmosphere—including CO_2 itself, as well as methane (CH_4) and nitrous oxide (N_2O). Our first project is located in the unfortunate 'poster child' of dead zones found where Mississippi and Atchafalaya Rivers drain runoff from the heartland of the continental United States into the Gulf of Mexico. However, working in this region and eventually others like it actually provides two direct benefits. First, it increases the efficiency of net CDR, because the lack of oxygen in the water column slows the consumption of organic carbon through zooplankton grazing or bacterial breakdown. Although several recent academic papers/preprints highlight this benefit (e.g., Rohling 2023, Raven et al. preprint), it has not been widely embraced by companies working in the space, and is one key differentiator for us. Second, the input of nutrients to this region provides a free and additional source of nutrients. We cannot overstate the fact that other approaches which sink biomass in open ocean regions will—in sharp contrast—strip nutrients from the water column and deprive downstream ecosystems of these nutrients, with potentially serious consequences. Hence we and others strongly recommend that all biomass sinking approaches should only be conducted in nutrient-enriched regions, as it is a win-win scenario: remove excess nutrients that cause dead zones, and also achieve more effective CDR.

Another unique aspect of our approach is that we directly disperse specific forms of 'helpful' phytoplankton into the ocean, which we first cultivate ourselves using photobioreactors that we manufacture ourselves. We have already established a warehouse cultivation facility that allows us to grow phytoplankton exponentially under ideal conditions, providing substantial initial efficiency. We use native diatoms with fast sinking rates, low to normal marine salinity tolerance range, and thick silica walls—factors that are more likely to lead to the sinking and preservation of carbon relative to remains of other 'harmful' forms of phytoplankton (e.g., dinoflagellates). Following our initial exponential grow out, we then release healthy native diatoms into the coastal ocean at relatively high densities with key mineral nutrients (especially silica). Success will mean diatoms outcompete harmful dinoflagellates, leading to higher sedimentation rates and higher levels of organic preservation once remains accumulate in deep water or marine sediments. An important additional point to make here is that export of diatom carbon and nutrients to deep water or sediments—in contrast to the fate of other types of phytoplankton in the water column—could have environmental benefits beyond CDR. These include reducing nutrient concentrations and cycling, as well as reducing consumption of carbon and oxygen in the water column. As we discuss below, we also think this will decrease the production of other greenhouse gasses.

We have preliminary data following seven diatom releases, with data from our final release providing clear evidence that our approach works. Using floating sensory arrays (which we will expand upon with our MRV), we directly measured increasing chlorophyll concentrations as well as net oxygen production (superimposed on natural daily cycles)—which are both indicative of high rates of growth, photosynthesis, and CO_2 uptake following our diatom release.



Following this success, our overall strategy is to expand our work and MRV deeper into the water column and outwards from shore. The oceans have to be a part of the CDR equation given their vast area and volume, and that the residence time of carbon in the deep ocean ranges from thousands of years (in the water column) to millions of years (in ocean sediments). Our end goal is to sink phytoplankton biomass as efficiently as possible and with the longest possible residence time. Although there is generally a trade-off between the two, the Gulf of Mexico and similar regions can provide a 'sweet spot' where it is possible to deposit carbon efficiently in comparatively deep sediments. To start, we will work on the extensive continental shelf found in the northern Gulf of Mexico, aiming to deposit carbon below the typical mixed layer depth in the region and below depths where it can be disturbed by storms. Our MRV will quantify any breakdown of carbon deposited in sediments. Following this, we will progress into deeper water depths, aiming to rapidly and efficiently deposit carbon. The northern Gulf of Mexico is again an ideal location for this, as the Mississippi River plume and formation of sinking fronts can transport biomass rapidly offshore and/or into deeper water.

In sum, we (1) grow native phytoplankton exponentially on land in warehouses using our own photobioreactors; (2) release them into nutrient-enriched dead zones where they photosynthesize, grow, and remove carbon dioxide; and then (3) track the sinking of their biomass carbon into the deep ocean or ocean sediments. As part of our IP strategy, we have filed two non-provisional patents that cover our process and methodology coupled with instrumentation. Our MRV approach uses a combination of methods in the water column that can be expanded to other types of mCDR—thereby advancing quantification methods for CO_2 drawdown—and will also measure carbon metabolism in sediments. A critical aspect of our MRV will directly assess associated ecosystem effects by measuring the production and consumption of the potent greenhouse gasses CH_4 and N_2O—which in our view is essential to all mCDR and land-based CDR.

b. **Project objectives:** What are you trying to build? Discuss location(s) and scale. What is the current cost breakdown, and what needs to happen for your CDR solution to approach Frontier's $100/t and 0.5Gt targets? What is your approach to quantifying the carbon removed? Please include figures and system schematics and be specific, but concise. Aim for 1000-1500 words.

We are building a rapid and efficient CDR solution that combines a technological 'boost' on land with arguably the most effective natural solution available in the ocean. In both settings, rates of photosynthesis, growth, and CDR by phytoplankton are exponential and powered by light—in contrast to solutions that scale linearly and/or require large amounts of external energy. We also do not produce waste products of any kind. Our overall approach is well-understood, and we have preliminary data showing successful CDR under real-world conditions. Our ongoing MRV will determine the ultimate efficiency of this. Finally, our approach can also have multiple co-benefits rather than negative impacts.

As noted above, these benefits are derived from working in the heavily impacted northern Gulf of Mexico to start. This provides scientific advantages for our work, and, as we describe below, we also aim to help the regional economy. Other regions around the country, continent, and world face similar environmental and resulting economic challenges, and so are future targets for expansion. However, the Gulf of Mexico provides enormous scale by itself given the extent of nutrient inputs, the extent of the dead zone, and other local environmental conditions. Other advantages of working in the Gulf of Mexico that will allow us to scale up include the presence of extensive local fishing fleets/boats, as well as abandoned fossil fuel infrastructure. Finally, our approach is modular in all aspects in that we can: (1) build more photobioreactors as needed, (2) disperse over larger areas and longer timeframes with additional boats (which we do not build ourselves, keeping costs low), (3) deploy additional MRV platforms with increasing dispersals in space and time.

Our overall approach is asset-light, which enables us to provide high-quality CDR at a competitive cost, as backed by our technoeconomic assessment. Our efficient photobioreactor manufacturing approach enables us to build out labs and cultivate phytoplankton while keeping costs low. By installing white LED lights as part of our manufacturing process we keep our electricity usage and costs down. Expenses embedded within our current cost breakdown are largely dominated by materials costs, especially with regards to silica (a key growth media ingredient for diatoms), and personnel. These personnel costs reflect our building partnerships with local stakeholders to directly conduct phytoplankton dispersals, and so we consider this a local economic benefit. These costs are also likely to decline dramatically after we initially equip local vessels for mCDR and scale up dispersals. Other highlights worth mentioning: (i) inexpensive warehouse rental costs in Louisiana keep CapEx low with regards to lab buildout and maintenance, (ii) the placement of our facility close to the local marina, and the close proximity between marina and dispersal locations, keep our transportation costs (including fuel) and project emissions low.

We believe that we can achieve Frontier's $100/t target for CDR during the delivery of our first project. Once at scale, we anticipate that additional CDR volumes will bring down cost to well below this threshold. Additional cost savings will come from streamlining our materials supply chain but this is not necessary to achieve $100/t; it is to achieve $29/t. To reach Frontier's 0.5 Gt target requires that we replicate this project in 50-100 other dead zones around the world, either by licensing our technology or setting up revenue sharing contracts with local stakeholders in various regions. With over 400 dead zones consistently occurring globally, working in many of these regions (using the first few as the basis for the rest) will enable us to remove 0.5 Gt of carbon per year. We are already developing a priority list for expansion, but our main focus is on scaling up in the Gulf of Mexico.

To ensure additional carbon is removed as a result of our methodology, we have developed a comprehensive MRV approach that is grounded in fundamental science. Our approach to quantifying CDR integrates time-tested techniques in oceanography (e.g., sediment traps) with newer approaches that can provide additional insight; the combination provides accurate, data-rich, shareable and scalable measurements. These data can also be easily provided to third parties for verification. More detail is provided in the MRV section below, but in short, we (1) quantify CO_2 removal through photosynthesis in surface waters via multiple sensors deployed on floating buoys, (2) quantify the flux of carbon-rich particles sinking through the water column by deploying underwater sensors and cameras at additional depths throughout the water column, and (3) quantify the flux to and preservation within deep waters and/or sediments using sensors, sediment traps, and measurements. This follows the latest approaches to quantifying ocean carbon flux deployed by the NASA EXPORTS project, and the combination of techniques provides multiple constraints on CDR. This will be complemented by daily boat surveys to map and track phytoplankton dispersals with flow-through or towed sensors, as we will be regularly dispersing phytoplankton and deploying or recovering equipment. We have also established partnerships with other start-ups (e.g., Ocean Aero) and academic institutions (e.g., Woods Hole Oceanographic) to gain access to novel autonomous underwater vehicles and CO_2 sensors that can help expand our MRV as we scale up.

Finally, we are venture-backed and ready to go today, as we have stood up our first large lab facility located in the location of our first project. This facility is now operational, so we are perhaps ahead of other companies in this space, making our technology readily deployable.

c. **Risks:** What are the biggest risks and how will you mitigate those? Include technical, project execution, measurement, reporting and verification (MRV), ecosystem, financial, and any other risks. Aim for 500-1000 words.

Technical: Working in the ocean presents several technical challenges that we are already addressing. First, we are operating at shallower coastal depths to start, and then working our way into deeper water, so that we can test our approach and then iterate and improve. Working with phytoplankton also presents technical challenges, and we do expect some failed dispersal events. However, we are exploring possibilities to accelerate sinking that may also provide an ocean alkalinity enhancement effect. As we note above and below, we have also designed our approach and equipment to be modular and relatively inexpensive, so that we can expand rapidly and adapt to changing conditions. We can easily stop, start, and expand CDR. We have also established partnerships with local fishermen and guides—in fact, our warehouse space is rented from a new minority-owned fishing and guiding company that also provides us expertise and boat access. Their deep local knowledge and access to vessel fleets are critical to our success. Many of these boats are idle due to economic and ecological issues with the local fisheries, and their owners and captains are interested in potentially working with us.

Project execution: Our work in the ocean does raise internal and external risks that might impact timing of project delivery. Internal risk is dominated by logistics, such as vessel-based work in waterways and bays, where a number of factors might keep these vessel(s) from being able to deliver. Separately, a lack of awareness by outside vessels could pose a separate risk should they come across our operations and/or floating buoys in the field and disturb them. Mitigation will be done by training our vessel operators appropriately and by retaining individually licensed captains who bring with them a wealth of knowledge of the area, minimizing vessel risk. Externally, weather including hurricanes can limit operations in our field area and in our warehouse, causing financial pain and delaying delivery of project execution. Mitigation will be carried out by monitoring weather patterns and prepping if necessary as well as communication with outside commercial fishermen so they are aware of our operations, if necessary, on a need to know basis. Finally, management oversight will be critical, to ensure movement around the delta is carried out effectively and beneficially.

MRV: Based on our ongoing venture-funded work, we know that we can grow phytoplankton efficiently in our photobioreactors, and we know from our preliminary data that they have high growth rates and CO_2 consumption rates once we release them into the coastal ocean. Our MRV approach will tackle two uncertainties about what happens next. First, we need to know how much carbon is exported into the deep ocean and/or continental shelf sediments. We will accomplish this using an integrated approach to MRV that will track the fate of phytoplankton carbon using a suite of complementary measurements. Our CDR approach is specifically designed to maximize export efficiency, as we are working in a high productivity area with low oxygen concentrations and with high sedimentation rates. We therefore expect our approach to be efficient overall, particularly when compared with work in other less suitable locations, but we need to verify this. One challenge is that after dispersal, ocean circulation will control where carbon ends up. However, sinking fronts can form in this region, which leads to rapid transport of surface waters and material to deep water (Qu et al. 2022). Alternatively, carbon may be deposited in sediments, with depth being a key determinant in how long it can potentially be sequestered; as we discuss below, our aim is for >50 m water depth to ensure lack of disturbance and mixing. A second uncertainty is that we need to know the fate of organic carbon if it is exported to continental shelf sediments. This will be accomplished through sediment-based measurements of carbon content, respiration, and greenhouse gas production. We do expect that some proportion of carbon is metabolized to CO_2 in sediments (~10-20% based on the literature). However, once we reach sufficient water depths, this will remain in the subsurface ocean and out of contact with the surface ocean and atmosphere.

Ecosystem: Many if not all CDR approaches need to contend with the production of the more potent greenhouse gasses methane (CH_4) and/or nitrous oxide (N_2O). Although these are regularly invoked as potentially negative side effects of biological mCDR—which they very well may be—this is often presented in a simplistic way compared with the complexity of their production *and* consumption in the ocean. Multiple processes and organisms produce and consume both gasses at different depths in sediment and the water column, and this complexity is not commonly understood among ocean/carbon cycle scientists who are not deeply familiar with the latest findings. However, our CSO is an expert in CH_4 cycling (e.g., Perez-Coronel and Beman 2022 *Nature Communications*) and especially N cycling (e.g., Beman et al. 2005 *Nature*, Beman et al. 2011 *PNAS*, and Beman et al. 2021 *Nature Communications*), and we will measure CH_4 and N_2O production in sediment in the dispersal area, as well as their potential production and/or consumption in the water column. This will provide a complete accounting of the major greenhouse gasses in response to mCDR, and, to our knowledge, is a key missing piece in all mCDR work to date. Scientific consensus is driving towards the fact that *all* CDR approaches need to address these gasses because their potency can offset CDR, so we will be ahead of the game (and also think there may be benefits in reducing N_2O production that other CDR approaches do not have).

Financial: Just four years ago, Ben's career at BP put him on the small technical evaluation team for one of the biggest CCUS projects in the world, at Teesside in the UK. BP, along with five partners, was investing $1.4 billion in infrastructure to pipe 2M tons of CO2 into porous rock under the North Sea.

In our minds, the project had significant technical risk; our estimate for how much CO2 the porous rock could hold varied by up to 5x. We also felt there was subsurface risk.

Considering the amount of technical risk, huge capex was financially exposed.

It's our belief that the Capex x Risk ratio isn't given enough attention across carbon tech.

We feel Lillianah is among the lowest marginal cost for CO2 removal, at $29 per ton, but what really separates us from other approaches is our ultra-low-capex. We simply don't put that much capital at risk. With just 3 dispersal locations, Lillianah could match Teesside's CO2 removal of 2M tons a year. Our capex on 3 locations is under $10M, and as low as $6M.

The correct way the carbon tech industry should be thinking about this – and the number to index upon – is "Revenue to Asset" ratio. If we just compare the North Sea CCUS Teesside facility vs Lillianah on Revenue-to-Asset, the difference is staggering. If, in both cases, we assume a price of $100/ton for CO2 removal, Teeside is 2M tons or $200M revenue, versus $1.4B capex. That's a ratio of 1:7 Revenue-to-Asset.

At Lillianah, where at our single first drop/dispersal site, at full pace, we can perform 720 drops a year, we can remove 720K tons of CO2 from the ocean. Which is $72M in revenue. But our capex would be around only $2M. So our Revenue to Asset ratio is $72M/$2M, or 36 to 1!

We believe all carbon tech CO2 removal companies should be reporting their Revenue to Asset ratio, not just their marginal cost per ton of CO2 removal. We believe companies with quite similar marginal CO2 removal costs could be wide apart on Revenue to Asset. Most CDR approaches need to incorporate construction and/or field operations into their plans. In many cases, unexpected execution related problems can unintentionally raise financial risk as any delay in execution tends to compound financial returns with respect to when volumes of carbon removed can take place. Luckily, a clear benefit of our approach is that we are CapEx light since our construction cost and project build-out cost are relatively minor. WIth that said, converting vessels from commercial fishing to phytoplankton dispersal CDR can be tricky with cost varying from vessel to vessel. Our remote operations generally pose a risk with respect to financial return as waves, wind, and weather can complicate vessel movement in the shallow waters of our area of interest. The pronounced seasonality of our project with most activity planned for March-October every year makes financing certain times of the year critical to our execution. Altogether, these components can inhibit when or how much carbon removal volumes can take place and/or be delivered. Mitigation of these issues will be carried out by careful execution and planning of vessel conversion to CDR boats, keeping our CapEx light strategy the same giving us a competitive advantage over our peers, having effective fieldwork operations management ensuring all vessel operators know who to talk to and where to go and why always, and weather monitoring. If weather is particularly bad any given day, even deciding to forego certain days can also help mitigate this risk.

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)*	3000 tons
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	a-1000 tons delivered by December 31 2024. b-2000 additional tons delivered by December 31 2025. c-Frontier should consider our contract for this agreement complete once 3000 tons have been delivered. If Frontier would like to expand this agreement by increasing purchase volume, we would be amenable to that [as we are confident we could deliver 5000 tons in calendar year 2025 (not just 2000 tons)].
Levelized Price ($/ton CO_2)* *(This is the price per ton of your offer to us for the*	[$192/ton USD]

tonnage described above)	

** 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).*

[redacted]

[redacted]

[redacted]

- [redacted]

[redacted].