Clairity Technology

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

Clairity Technology

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

Culver City, California, United States

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

Glen Meyerowitz

Brief company or organization description <20 words

Clairity Technology develops systems for direct air capture of carbon dioxide. We create dilute CO2 streams for durable sequestration.

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.

Clairity Technology develops systems for direct air capture (DAC) of CO2 from the atmosphere for durable sequestration. We implement a solid sorbent approach, where honeycomb substrates are coated with a proprietary mixture of carbonate salts and other chemical species to adsorb CO2 from the air. Our unique approach generates a low-purity CO2 stream for durable sequestration, unlike other approaches to DAC that generate high-purity CO2 streams. The focus on partial enrichment of CO2 is a priority innovation area identified in the Frontier RFP. We are excited to be one of the few companies developing and actively scaling in this critical innovation area.

Clairity's Approach to CDR

Our unique approach to direct air capture will enable scalability of cost-effectiveness that is not achievable with other approaches. Our focus on partial enrichment of CO2 targets an end purity of approximately 20% CO2 and 80% air in the fluid stream that leaves our direct air capture (DAC) system. This enables rapid scalability as we can deploy facilities and deliver tons of CDR quickly and with a lower capex.

Clairity uses a solid sorbent approach. A honeycomb substrate is used to provide increased surface area for the air contactor while reducing the pressure drop of the system. This is coated with a proprietary mixture of carbonates and other chemicals, which serve as the sorbent to adsorb CO2. The specific chemical reaction depends on the ambient conditions, such as temperature and relative humidity. The below figure shows example potential reactions between K2CO3 and CO2.

$$K_2CO_3 + 1.5H_2O_{(g)} \rightarrow K_2CO_3 \cdot 1.5H_2O$$
$$\Delta H_{300\,K} = -101.0\ \mathrm{kJ/mol} \qquad \text{(R1)}$$

$$K_2CO_3 + CO_{2(g)} + H_2O_{(g)} \rightarrow 2KHCO_3$$
$$\Delta H_{300\,K} = -141.7\ \mathrm{kJ/mol} \qquad \text{(R2)}$$

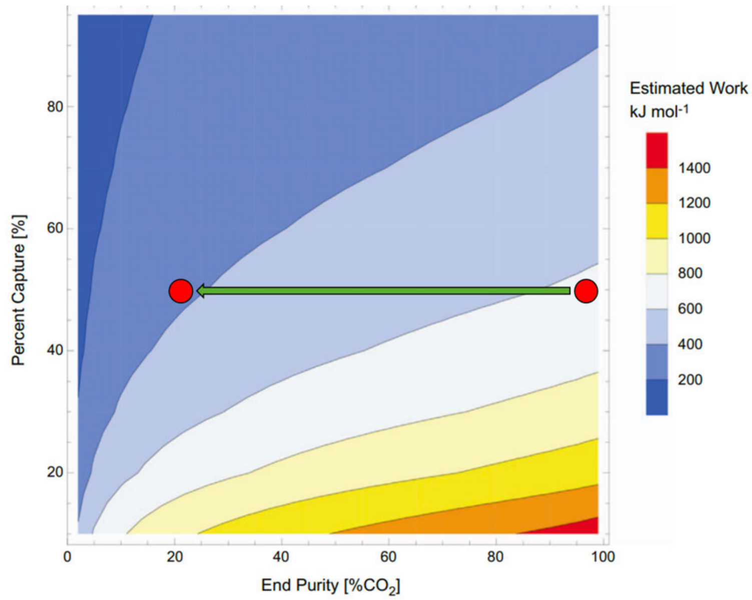
$$K_2CO_3 \cdot 1.5H_2O + CO_{2(g)} \rightarrow 2KHCO_3 + 0.5H_2O_{(g)}$$
$$\Delta H_{300\,K} = -40.7\ \mathrm{kJ/mol} \qquad \text{(R3)}$$

Air is blown through the reactor to sufficiently saturate the sorbent with CO2. Once the adsorption phase is completed, the reactor seals and regeneration of the sorbent occurs. We use a low-temperature, thermal regeneration approach in which the reactor is heated to a target temperature to desorb the CO2 from the sorbent. The CO2 is collected and concentrated, where it can then be handed off to a partner for durable sequestration. The reactor is unsealed, and the process can begin again.

Partial Enrichment of CO2 – Energy Impact

CDR will be a tremendously energy intensive industry, regardless of how it is performed. Current technologies require tens of GJ per ton of CO2 removed. To scale, this technology must reach energy efficiencies of approximately 5 GJ / tCO2. For smaller systems, a higher marginal energy cost per unit of CO2 will have a smaller impact. As systems scale in size from small demonstration plants that can remove thousands of tons of CO2 to larger systems that can remove millions to tens of millions of tons of CO2, these marginal energy differences will be magnified.

Research from Dr. Jennifer Wilcox, the Principal Deputy Assistant Secretary in the Office of Fossil Energy and Carbon Management at DOE and the Presidential Distinguished Professor of Chemical Engineering and Energy Policy at the University of Pennsylvania, demonstrates this. The following figure shows calculations of the estimated real work required to generate a given end purity of CO2 via direct air capture from air. [3]



Assuming a nominal percent capture, the amount of work to generate a high-purity (>99% pure) stream can be 2-3x greater than the amount of work to generate a low-purity stream. We can assume approximate energy requirements of 700 kJ / mol for a high-purity stream and 300 kJ / mol for a low-purity stream, a difference of 400 kJ / mol. When this energy difference is scaled to gigaton removal levels, the energy savings of a low-purity stream exceed 2,290 TWh of energy. This difference represents over 8% of the total energy consumption of the entire United States!

Partial Enrichment of CO2 – Capital Impact

Beyond the operational expenses, the capital expenses of a low-purity DAC system are dramatically reduced when compared with a high-purity system. High purity systems require vacuum pumps, steam generators, and more to remove the air and other impurities from a reactor vessel. They are constructed from welded steel vessels and with tremendous amounts of concrete for the assorted pressure vessels and high-purity components. This results in a commensurate increase in lifecycle emissions for a high-purity DAC system, compared with our technology. For a low-purity system, this is not necessary, and the system can be constructed using traditional building equipment, such as dimensional lumber and HVAC ducting.

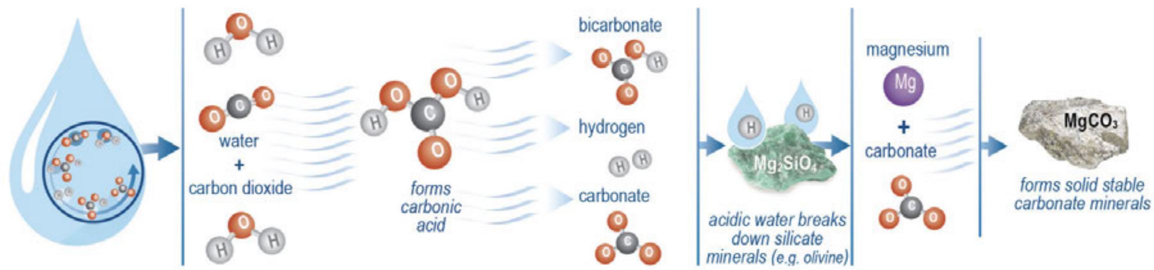
If the largest vacuum chamber in the world, the Space Simulation Vacuum Chamber at NASA Glenn, were converted into a reactor vessel for direct air capture, it would have an estimated capacity of 163,750 tons of CO2 (tCO2) / year. This is assuming an average sorbent cyclic capacity of 150 mmol CO2 / L / cycle. To achieve the scale of 10 Gt CO2 removed annually, it would require over 60,000 identical vacuum chambers - a tremendous undertaking with an equivalently large emissions of CO2 from the concrete, steel, and other materials that would be required to build these facilities.

For a given CDR capacity, it is possible to estimate the required reactor volume assuming a constant sorbent capacity. Once the reactor volume is calculated, one can calculate the amount of steel that would be required to construct this as a vacuum chamber for a high-purity system or the required amount of lumber to build a low-purity system. Our analysis demonstrates that there are hundreds of millions of dollars in capex savings due to the overall simplicity of a low-purity system at gigaton scale.

This reduction in systems complexity also results in lower design and engineering costs, and reduced project risks. Deploying a novel technology is always a challenge, and complex systems are harder to deploy smoothly, as we have seen with numerous high-profile delays in DAC projects to date. We have seen that the inherent simplicity of our systems allows for more straightforward deployment.

Partial Enrichment of CO2 – Sequestration & Storage

Low-purity CO2 streams can be durably sequestered for >1,000 years, similar to high-purity CO2 streams. There are a number of sequestration pathways, including, but not limited to, geologic sequestration via injection, enhanced weathering, and carbon mineralization. The following figure, from the Carbon Mineralization Roadmap, follows carbon molecules through the mineralization process. [4]



While this is only one potential pathway for sequestration, it demonstrates a key point that adequate CO2 molecules are necessary to sustain a stoichiometric chemical reaction. The purity of the CO2 stream is an independent factor, and the fluid stream mass flow rate can be adjusted to maintain an adequate molar flow of CO2. The partial pressure of the CO2 impacts the kinetics of the reaction, depending on the specific reaction the impact of partial pressure may be small or large. The absolute pressure of the fluid stream can be adjusted to increase the partial pressure of CO2 in a low-purity system to achieve the same partial pressure.

Summary

Carbon dioxide removal at gigaton scale is a necessary solution to mitigate the worst effects of climate change. With a focus on scalability, low-cost, and energy efficiency, Clairity Technology is bringing to market a novel technology to scale a direct air capture solution focused on partial enrichment of CO2 streams. We believe this approach offers hundreds of millions of dollars in savings at scale, and that the simplicity of the systems allow for increased speed of scaling.

Our team of best-in-class scientific and engineering talent has the expertise and skillset to solve the underlying technical problems and deliver hardware. We have strong partnerships to supply high-quality materials and to enable sequestration of our CO2 streams. Combined, these factors will enable Clairity to succeed in being part of the portfolio of solutions to remove billions of tons of CO2 from the atmosphere in the coming years.

References

[1] Cumulative CO_2 emissions by world region, Our World in Data. https://ourworldindata.org/grapher/cumulative-co2-emissions-region?stackMode=absolute

[2] IPCC, 2022: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844.

[3] Wilcox, J et al 2017 Environ. Res. Lett. 12 065001

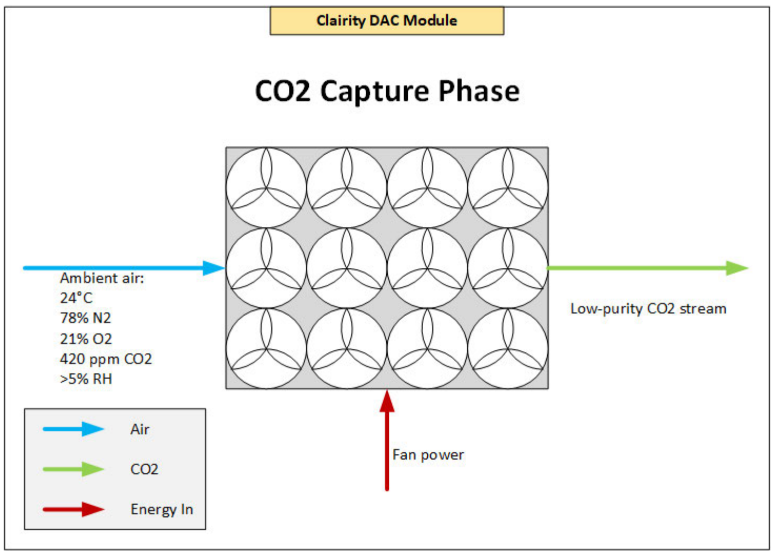
[4] Sandalow, D.; Aines, R.; Friedmann, J.; Kelemen, P.; McCormick, C.; Power, I.; Schmidt, B.; Wilson, S. Carbon Mineralization Roadmap, Columbia University, 2021

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.

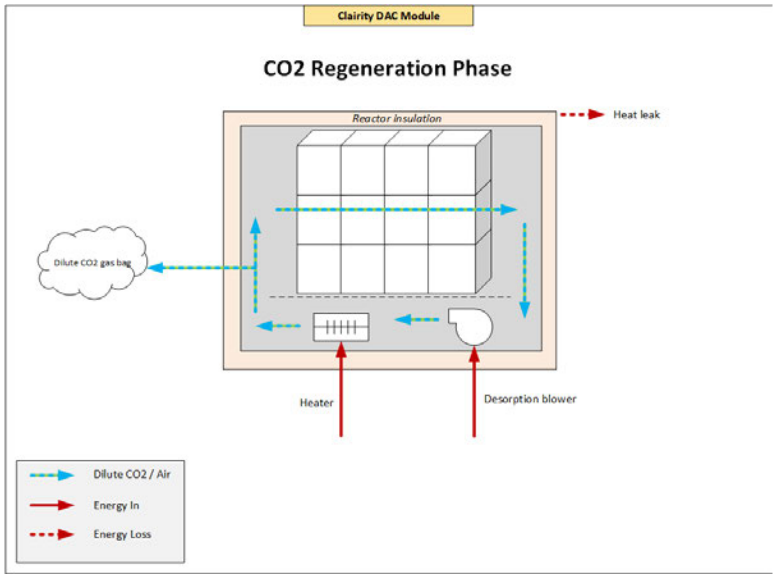
Clairity Technology is proposing a pilot demonstration plant that will remove net 405 metric tons of CO2 from the atmosphere by April 2025. Our sequestration partner is CarbonBuilt, a low-carbon concrete startup that develops technology to durably sequester carbon dioxide by injecting CO2 into concrete while it cures to where the CO2 mineralizes. This project will be co-located at an existing CarbonBuilt site, located at the Blair Block facility in Childersburg, Alabama.

All our facilities will consist of a modular direct air capture (DAC) system, with multiple identical modules. The majority of the equipment will be independent for each module, such as fan and instrumentation. There will be some shared equipment between all modules, such as the gas recovery and storage systems.

The following figure shows the module process diagram during adsorption. A fan blows air over the reactor at a given flow rate, allowing the CO2 from the air to be adsorbed by the sorbent. Once the sorbent has been sufficiently saturated, the reactor will switch from adsorption to desorption.



In desorption, the reactor seals off from the outside and a thermal regeneration begins. A heat exchanger inside the reactor is used to increase the reactor temperature to a target temperature, which may vary depending on the specific chemical sorbent used. As the sorbent regenerates, CO2 will be evolved from the reactor bed. The CO2 will mix with the ambient air inside the reactor vessel and slowly fill a gas recovery bag. The CO2 concentration within the gas recovery system will slowly increase over the course of the regeneration phase, until the sorbent is fully regenerated.



The CO2 in the gas recovery system is passed along to our sequestration partner, CarbonBuilt, for durable sequestration via injection into concrete. We use a low-pressure blower to move the fluid through a pipe that interfaces between the two systems. The pipe is instrumented with a flow meter and CO2 concentration sensor which allow for real-time and continuous monitoring of mass of CO2 that is transferred to CarbonBuilt for sequestration.
The following equation is used to calculate the total mass of CO2 that is transferred for sequestration over the lifespan of the project, based on the instrumentation in the transfer pipe.

$$mCO_{2,Y} = \int_0^Y \dot{m}_{fluid} \bullet X_{CO2} dt \tag{1}$$

where:

$mCO_{2,Y}$	Mass of CO2 sequestered	ton CO2
$\dot{m}_{fluid}$	Bulk flow rate of fluid passed from removal system to storage	kg / sec
X_{CO2}	CO2 weight fraction in the fluid stream for sequestration	kg CO2 / kg fluid
Y	Monitoring period during which credits are produced	days

CarbonBuilt has existing operations in partnership with Blair Block in Childersburg, Alabama. Blair Block produces and sells concrete masonry units in a variety of sizes and on a number of different lines. CarbonBuilt technology is used to retrofit these existing lines to sequester CO2 by injecting it into the raw materials that produce the blocks.
The current cost of this CDR is approximately \$805 / tCO2. Given the small size and shortened system lifetime, compared with future planned CDR projects, the levelized capital and fixed operational costs are a higher share of the total budget than expected in the future. Specifically, these costs represent about two-thirds of the proposed project cost, compared with less than half for future projects. We expect the capital and fixed operational costs to reduce by approximately 90% as our

technology scales.
The expected energy usage for this project is approximately 13.3 GJ / tCO2. A sensitivity analysis shows that approximately 65% of the required energy is for regeneration of the sorbent; approximately 20% of the required energy is for the primary fan for adsorption; and the remaining energy is for systems operations. We are actively exploring techniques to reduce the energy of the system, including by reducing the thermal mass of the solid sorbent substrate and lowering the regeneration temperature.
Primary fan energy can be reduced by optimizing the solid sorbent substrate and the reactor design. It is known that a range of substrates can be used for air filtering applications, based on extensive research for environmental, automotive, and industrial applications. Increasing or decreasing the cell density of a substrate impacts both the specific surface area and the pressure drop. Higher specific surface areas result in larger pressure drops. Optimizing these values for direct air capture applications is a challenging problem with a large parameter space, as the ability to load sorbent without clogging cells is also impacted by the cell density.

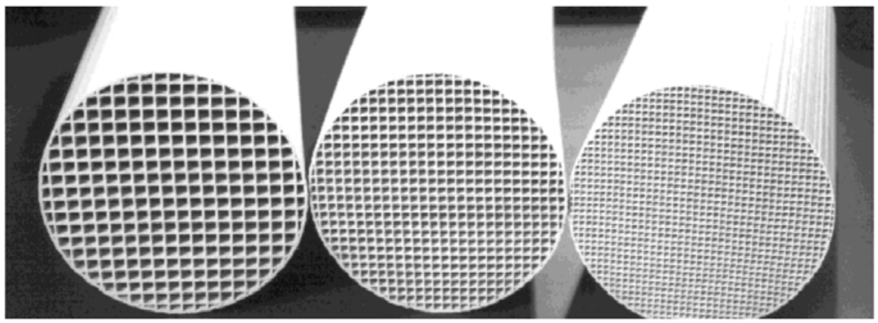


Figure 1. Photograph of monolithic catalyst supports with different cell densities.

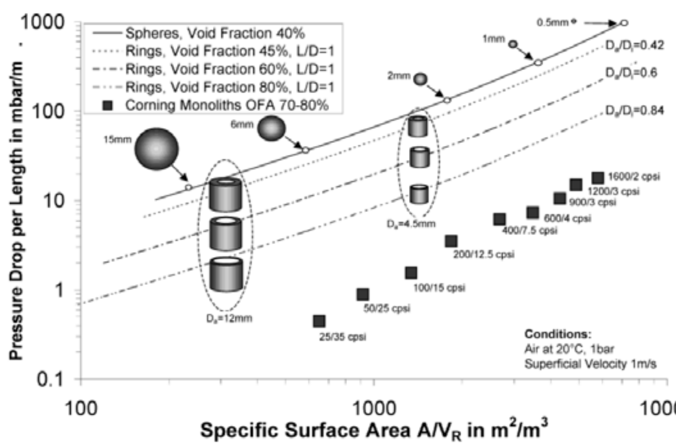


Figure 2. Pressure drop vs specific geometric surface area of monolithic structures, spheres, and rings. Data are for air at 20 °C and 1 bar and a superficial gas velocity of 1 m/s (at STP). Monolithic data are for commercial and developmental products (the notation is cell density in cpsi and wall thickness in $^1/_{1000}$ in.).

Regeneration of the sorbent is a very energy intensive process – regardless of the energy source. Whether the energy comes from thermal, chemical, electrical via Joule heating, or other sources, the amount of energy required to break chemical bonds is independent of source. Additionally, the substrate often needs to reach a given target temperature in order for the regeneration reactor to be energetically favorable.

$$Q = mC\Delta T \tag{2}$$

where:

Q	Thermal energy for heating	J

m	Mass of the sample to heat	kg
C	Specific heat capacity of the sample	J / kg°C
ΔT	Change in temperature of the sample	°C

Thermal energy for heating can be reduced by decreasing the mass of the sample, the specific heat capacity of the sample, and the change in temperature of the sample. We are working to decrease all three by developing improved substrates with lower densities and lower specific heat capacities and improving the sorbent chemistry to enable regeneration at lower temperatures.

Combining these expected improvements, we estimate that the total energy required for our direct air capture process will decrease by more than 50%, from 13.3 GJ to approximately 6 GJ per tCO2. We expect these energy efficiencies and economies of scale to drive the cost of our CDR to below $100 / tCO2, while enabling larger and larger scale.

Strategic partnerships will enable Clairity to be part of a portfolio of solutions that enable gigaton removal of carbon dioxide from the atmosphere for durable sequestration. We do not expect any single company to support this entire industry, or to be able to remove billions of tons of CO2. Partnerships to enable advanced materials development, sourcing of key and critical components, and scalable and global durable sequestration will all be critical to achieving the scale required to mitigate the worst effects of climate change.

Clairity plans to engage with policy leaders at the local, federal, and international stage to advance policy to advocate for and help scale all approaches to carbon dioxide removal. Only with significant support from both the public and private sector, will the entire CDR industry scale to meet the ambitious goals demanded by this problem.

Beyond the demonstration pilot plant, Clairity is in active discussions with other sequestration partners for future DAC facilities. We expect to bring these additional facilities online starting in 2024 to augment the gross CDR capacity above the single facility in this project. Clairity's first 405 tons of CDR, regardless of facility location, will be delivered to Frontier as part of this prepurchase. This may result in an early delivery of CDR to Frontier.

Given our focus on partial enrichment of CO2 we have seen lower capital cost of building new systems which, compared with other technologies. We expect these lower costs will accelerate deployment of our hardware and improve scaling. Our team includes world-class engineering talent who have experience building the most complex hardware for aerospace industries and we are leveraging those skillets to scale direct air capture production and deployment.

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.

There are several risks for this project that we are actively working to mitigate.

The largest technical risk is the stability of our sorbent in the real-world environment. It is not known what the lifespan of a given sorbent is and the impact of environmental variables, such as temperature and humidity swings, is hard to quantify. We have performed extended duration testing in a laboratory environment which demonstrates the stability of our sorbent. We plan to perform additional testing to understand the stability of the sorbent across a wider range of operating conditions.

An additional mitigation technique for understanding real-world performance of our sorbent is to collaborate with US DOE laboratories for this work. We have been in contact with Dr. David Sholl at Oak Ridge National Lab, who has resources for simulating extreme environmental conditions across the US and we plan to operate our systems in those settings to collect performance data.

An additional technical risk is the amount of water that may be adsorbed by our sorbent. In laboratory testing, we have seen a range of H2O adsorption, depending on the ambient temperature and relative humidity of the incoming air stream. As the amount of water adsorbed by the sorbent increases, the energy required to regenerate the sorbent increases. We do not know the exact amount of water that will be adsorbed, or the energy required to desorb water from the sorbent. We are actively exploring methods to differentiate between weight gains associated with bicarbonate formation and water uptake at different relative humidity values. In addition to modifying the material properties to reduce water update, we have engineering approaches to mitigate the impact of water desorption on our system performance. We are exploring the integration of a condenser loop into the desorption system to remove water and maintain a target water vapor pressure within the reactor at all times. An operational risk associated with this project is potential materials sourcing problems due to supply chain constraints. Over the last several years, supply chain bottlenecks have been present across many industries causing delays and increased lead-times. We are in frequent communication with key suppliers and vendors to understand their timelines and maintain an accurate project schedule. This project will be the first-of-a-kind where direct air capture (DAC) is used to generate a partially enriched CO2 stream for sequestration. This novel technology presents MRV challenges, as it does not align with existing frameworks. We plan to use rigorous technical and scientific methods, including real-time and continuous monitoring with sensors, to quantify the CDR of this project to mitigate this risk. Access to clean energy with a low carbon intensity is a project execution risk as our technology scales. For CDR approaches to scale, these technologies will consume a significant portion of global energy production. This will require a commensurate scale-up in clean energy, such as hydropower, geothermal, solar PV, and more, to ensure that the energy used for CDR does not contribute to the problem we are looking to solve. We are in early conversations with potential partners to explore the development of new solar farms to support our projects or co-locate with geothermal production sites. Beyond the known risks here, we expect there to be many currently unknown risks that will impact our development and scaling. We feel that the best way to mitigate these, and all future risks, is to assemble a team of world-class scientists and engineers who face problems with a first principles approach based on rigorous testing, analysis, and data collection. We strive to be data informed in all the decisions we make and are confident that we will be part of a portfolio of solutions that can remove billions of tons of CO2 from the atmosphere!

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)	405 tons
Delivery window (at what point should Frontier consider your contract complete? Should match 2f)	April 2025
Levelized Price ($/ton CO_2)* (This is the price per ton of your offer to us for the tonnage described above)	$805

** 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).*