Holocene

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

Holocene Climate Corporation (dba “Holocene”)

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

Knoxville, TN; United States of America

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

Keeton Ross (keeton@theholocene.co)

Brief company or organization description <20 words

Holocene is a direct air capture (“DAC”) technology developer and carbon removal service provider developing & deploying a scalable, low-temperature, aqueous carbon removal system.

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. Aim for 1000-1500 words.

Holocene is designing and deploying a novel thermochemical approach to DAC that involves an aqueous (liquid) CO_2 loading process and a low-temperature (~100–120℃) regeneration/CO_2 unloading process, which has been optimized for reliability, scale and cost.

Our system leverages a continuous process designed around two chemical loops. The first loop is focused on CO_2 loading, where selectivity, durability, and mass transfer are paramount. The second is focused on CO_2 unloading, where energy delivery and energy efficiency are the focus. Within the first loop, air comes into contact with an aqueous solution that is loaded with the first working chemical, an amino acid. The amino acid increases the solution's ability to uptake CO_2 from air, and by leveraging a high surface-area-to-volume ratio contactor, the system moves CO_2 from ambient air into solution.

In the second loop, the CO_2-loaded amino acid solution comes into contact with the second working chemical, a guanidine, where a transfer reaction occurs and the CO_2 moves from the amino acid to the guanidine, forming an organic carbonate salt. This new compound precipitates out of solution, allowing for the organic carbonate salts to be separated into a solid form that is heated to 110℃ to regenerate the CO_2. Each of these two working chemicals is recovered and re-used in the process. The novel combination and application of these two organic working chemicals, and the unique characteristics of the organic carbonate salt regenerating at lower temperatures than traditional inorganic carbonates (~900℃) is what differentiates Holocene's technology from incumbent approaches.

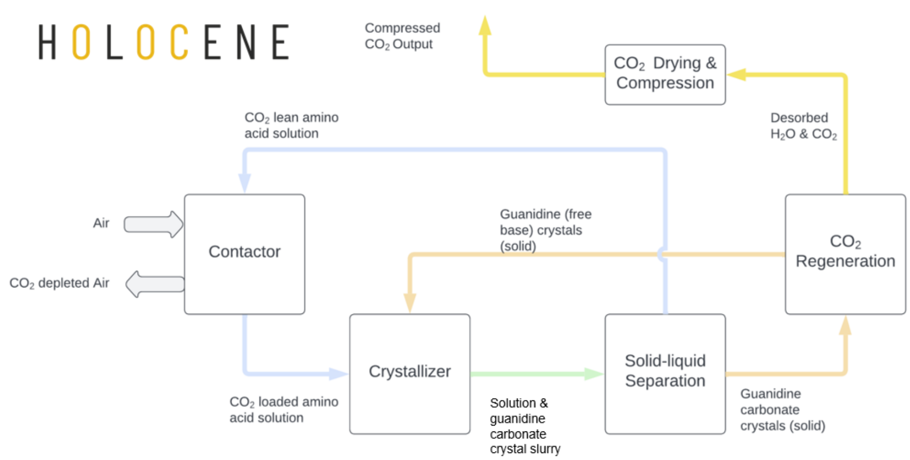

Figure 1: Block flow diagram of Holocene DAC process

[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.

Additionally, several variants of the proposed chemistry exist; the different possible pairings of amino acids and guanidine used form a suite of solutions that can be further optimized across energy, cost, and scale. Holocene and its partners continue to develop new materials to drive system performance across key characteristics, such as CO_2 uptake rates and reaction energies.

To our knowledge, this is the only solvent-sorbent DAC system involving an aqueous absorption and low-temperature regeneration being developed today – creating exciting whitespace for step-change technological improvements.

Holocene is unique in its differentiation – providing it the opportunity to deliver on the lofty ambition that Frontier has established of >0.5Gtpa of CO_2 removal at an all-in cost of <\$100/t-CO_2.

These differentiators include:

- **Our team:** our founders have helped design and build the world's first DAC facilities (e.g., Hinwil, Orca) and carry all of the learnings and capabilities that come from those years of experience. Beyond our founding team, our technical team brings decades of experience within chemistry, chemical engineering and mechanical design, developing and scaling hard-tech and chemical technologies at the world's leading technology and scientific institutions.
- **Our technology:** the application of *organic* chemicals, vs. *inorganic* chemicals within a solvent-based DAC approach is our fundamental technology differentiator and a truly novel approach to DAC. This differentiator brings with it several key advantages – the ability to design a continuous system (in contrast to batch processes for solid adsorbents), lower energy requirements, more flexible energy inputs (e.g., renewables, low-grade waste heat), and an overall higher net negativity of our system (LCA shows <10% loss in net removals). We believe this approach brings the best of both worlds from incumbent approaches, specifically benefiting from advantages associated with low-temperature material regeneration (as in Climeworks' technology) and continuous process in and scalability (as in Carbon Engineering's technology).
- **Our supply chain:** our technology design enables a supply chain across key equipment, materials/chemicals, and utility inputs that is robust and highly scalable. Within our system design, our technology can be built and scaled from existing industrial chemical equipment supply chains and does not require any net-new equipment innovation (e.g., electric calciners) to scale. Our chemical feedstocks are organic – meaning they are made entirely of abundant Carbon, Hydrogen, and Nitrogen atoms and are non-toxic. Lastly, our low-temperature requirements afford flexible energy and utility inputs that allow for optimization around siting and footprint + cost-optimized energy inputs (e.g., renewables, low-grade heat, steam, etc.)
- **Our supporters:** we are fortunate to have world-class supporters across our technical and company building priorities. This includes nearly 6 years of existing research and development on the application of guanidine carbonate salts from Oak Ridge National Laboratory, numerous technology incubators and development awards (XPRIZE student award, R&D 100 Award, DOE grant), and numerous business / company development awards (Breakthrough Energy Fellows, University of Tennessee's Spark Accelerator, Innovation Crossroads) that have afforded Holocene more than \$5Mn in cumulative non-dilutive funding to develop our technology and business.

While we are excited about our potential, there remains a great deal of work ahead of us – namely, our ~1300tpa "Pilot" project that we are excited to offer CDR services from to Frontier.

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.

Holocene is pursuing a feasible, yet ambitious, scaling path on our journey to making a meaningful dent in atmospheric CO_2 concentrations. This scaling path is grounded in our experiences and learnings from building and commercializing the world's first DAC facilities.

An important step in that journey is our first commercially relevant, or ~1,300tpa "Pilot" facility. This "Pilot" will serve multiple purposes in our business and technology development – including commercial (e.g., CDR services), research & development, partnership, project development, and educational / community services.

This Pilot facility is planned for siting in Eastern TN (e.g., Knoxville) and will be developed in collaboration with several of our existing supporters we are excited about building deeper collaborations with – this could conclude, but is not limited to, the Tennessee Valley Authority (TVA) and local economic development organizations (e.g., TAEBC). The target site will be designed to utilize waste heat from local industrial facilities and will source its electricity from one of many hydro-electric, clean power sources that Tennessee has to offer.

Regarding the end-of-life of these permanently sequestered removal tonnes, we are designing this project to be development-oriented and deliver learnings that will translate to larger scale deployments. As such, we are focused on permanent geologic injection in the surrounding regions – like Southern Illinois (e.g., Mt. Simon Sandstone) and the Gulf Coast (e.g., Alabama, Louisiana) – essentially, distances within a reasonable radius to truck captured CO_2 to the sites of developed injection networks. In parallel, however, we will be developing alternate sequestration pathways of (a) longer-term, TN-based sequestration sites (b) near-term, smaller-scale permanent mineralization of CO_2 within concrete. We have included application addendums on both sequestration pathways for the reviewers to consider.

The removed carbon will be quantified in accordance with standards developing in the broader DAC space – namely, monitoring of captured tonnes by measuring the flow and quality of CO2 from our plant and through the entire lifecycle accounting of net removals, and careful monitoring of geologically injected carbon dioxide. Holocene values the collaborative nature of the broader DAC and CDR space, and will work in accordance with existing standards, while identifying opportunities to advance the field by developing MRV approaches that are relevant to Holocene's specific technology and deployment focus.

For this "Pilot" project – sized at a rather modest scale of ~1300tpa – the costs of carbon removal services are notably higher than what we expect to deliver with our larger commercial and world-scale facilities. Within this application, we are offering Frontier 332 tonnes of CDR at a price of $1505/tonne-$CO_2$.

With respect to cost, we are confident in our technology and system's path to reaching near or below $100/tonne CDR services. The path from this "Pilot" to those cost levels does not run through any net-new scientific inventions or non-existent industrial supply chains. Rather, the costs for this project are driven higher primarily due to (1) shorter facility lifetimes (e.g., 10 vs. 30+ years), (2) higher equipment and material procurement unit costs at smaller scale, (3) the absence of economies of scale and learning at this "Pilot" facility scale (e.g., classic chemical engineering plant scaling behavior), and (4) modest expected improvements on core system performance metrics (e.g., energy, throughput).

As expected, the costs of this project are dominated by fixed OPEX costs and CAPEX amortization due to the small size of the project. Namely, ~65% CAPEX amortization, ~25% fixed OPEX, with only ~5% driven by variable OPEX and ~5% driven by transport and sequestration costs.

We believe that the "white-space" that is low-temperature, solvent-sorbent system design that Holocene is entering creates significant potential for achieving and even surpassing current expectations for system performance and cost, without the need to create net-new supply chains.

With respect to scale, we see no fundamentally prohibitive limiters to achieve the scale ambitions of >0.5Gtpa that Frontier has established. The core limiters to be aware of are:

- **Inputs** - our system leverages freshwater, thermal, and electrical energy. As demonstrated in later portions of the application, the thermal and electrical energy requirements improve upon incumbent technologies and the water requirements sit below those of comparable and emerging users of water (e.g., cities, steel, agriculture, green hydrogen). (Non-Limiting)
- **Materials** - as noted, amino acids and guanidines perform the majority of the CO_2 transfer throughout our system and Holocene relies on established industrial equipment supply chains. The required amounts of amino acids and guanidines are quite low (e.g., <0.1% chemical-to-CO_2 removal ratios), amino acids production supply chains are well-established for other industries, and guanidine production pathways are not prohibitive in their process or precursor requirements. (Non-Limiting)
- **Sequestration** - at millions-of-tonnes of removal, Holocene expects to rely on the vast geologic injection basins that are currently being developed for CO_2 sequestration. At smaller scales, Holocene is excited about CO_2 valorization applications offering permanent storage solutions (e.g., concrete, carbon fiber) but will not rely on these pathways to deliver on Frontier's scale ambitions. We understand that partnerships throughout the value chain will be core to delivering this level of CDR scale and have already begun engaging with sequestration providers who we expect to deepen relationships with as we grow our impact. (Non-Limiting)

Bringing together cumulative experiences in DAC on tech and market development with new chemistry, Holocene is well placed as an "additional shot on goal" for permanent CDR. Our experienced team of DAC and CDR veterans and business builders has strong conviction in our path toward affordable, scalable, effective, and low-impact DAC and we look forward to engaging with the Frontier team and broader CDR community on this journey.

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.

Holocene has conducted a thorough risk assessment and we have grouped our largest project uncertainties into four key areas:

Technical – our team continues to iterate on and optimize the chemical performance and process design of our system, this includes but is not limited to, optimizing chemical recovery rates (e.g., system inefficiencies and losses) and optimizing for yield and energy performance based on the two working chemicals chosen for the system pairing. A technical roadmap has been developed to overcome these challenges.

Funding – while our team has secured significant non-dilutive funding already, we are aware that additional funding will be required to support the pilot project. This funding is expected to come from both non-dilutive sources (e.g., government, grants, customer purchase agreements) and dilutive source (e.g., venture capital). Our team is confident that their track record, company performance, and networks can deliver on these financing needs when the time is right, and early funding conversations are underway.

Supply Chain (chemicals, equipment) – our chemical supply chain relies on one at scale chemical (e.g., amino acid) but one not-yet at scale chemical (guanidine). Scaling the production of guanidine is a current priority of our team and a project supported by current and pending grants(e.g., Breakthrough Energy Fellowship, DOE grant,) – we have been conservative in our TEA assumptions to account for this uncertainty. Additionally, equipment procurement is always a potential risk in project execution. We aim to mitigate this in two ways: (1) limiting the use of custom-made equipment and chemicals and focusing on integrating classical process equipment into our plant designs and (2) we've prioritized finding and engaging with suppliers early on, including through industrial partners.

Siting & Sequestration – we plan to site our first project in TN, but we do not yet have the site or sequestration partners secured. Given this uncertainty, we have listed both geologic injection (primary) and long-duration storage utilization routes (e.g., concrete) as potential routes for our CO_2 and have filled out both supplements accordingly. We've begun several partnership conversations and technical explorations on this front as part of our TN DAC Hub application and we will use that discovery and momentum to crystallize sequestration and siting as the project nears its commissioning date.

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)*	332
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	CY2026
Levelized Price ($/ton CO_2)* *(This is the price per ton of your offer to us for the tonnage described above)*	$1505 ($500K total)

** 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).*