[Carboniferous]

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

Carboniferous Inc.

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

4200 San Jacinto St, Houston, TX 77004

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

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Brief company or organization description <20 words

Carboniferous is developing approaches to sequester terrestrial biomass in anoxic marine basins as a means for durable and scalable CDR.

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.

Throughout Earth history, one of the principal mechanisms by which atmospheric CO_2 concentrations have declined from hothouse conditions is the burial of organic carbon in anoxic marine basins. Carboniferous's Anoxic Biological Carbon Sequestration (ABCS) process is designed to safely accelerate the natural process of organic carbon burial by collecting and processing agricultural byproducts and storing them in deep, hypersaline, anoxic basin at the bottom of the ocean in the Gulf of Mexico.,

Our CDR approach is designed to maximize the efficiency of biomass preservation through both our choice of biomass source and our targeted storage location. Most terrestrial biomass and crop residues are composed of lignin, cellulose, and other structural polymers that are relatively resistant to chemical and microbial breakdown. Some of these materials, like lignin, are particularly difficult to degrade in the absence of O_2 (Marchand et al., 2005). Anoxia also slows the breakdown of terrestrial materials by restricting the activity of animals like wood borers that physically degrade biomass, and it reduces the energy available to microbes. Deep hypersaline anoxic basins take this effect even further, generally slowing metabolic rates (Amano et al., 2020) and limiting life forms to extremophilic bacteria and archaea. Therefore, overall, terrestrial biomass storage in anoxic environments should represent an optimal scenario for efficient biomass preservation.

The sources of carbon for the ABCS process are crop byproducts, including sugarcane bagasse (the pulp remaining after sugarcane processing) and corn stover (stalks, leaves, etc.). These materials fix large amounts of carbon every year, with one tonne of dry terrestrial biomass embodying approximately 1.6t of CO_2e. Currently, most non-grain biomass is tilled back into the soil to decompose or burned, releasing the fixed carbon back into the atmosphere and contributing to the seasonal upward jag in the Keeling curve. Our approach mitigates the return of part of this biomass to the atmosphere.

Sequestration Process: Biomass is gathered and transported to a local facility where it is processed to enable more efficient transportation. The biomass is loaded onto a barge, transported down the Mississippi, and placed into a deep, hypersaline anoxic basin located 2,400 m below the surface of the ocean and 130 miles south of Louisiana.

Carboniferous's system falls within the BiCRS pathway and is best in class because it both leverages existing resources and is grounded in well-established fundamental science, giving it a high probability of achieving gigatons of sequestration. As discussed below, the approach is scalable, durable, affordable, and equitable.

Scalability: ABCS can be deployed at scale because crop wastes and the infrastructure to process and transport them already exist. Of any CDR technique being actively considered, terrestrial biomass sequestration in anoxic basins has the highest potential for both short-term implementation and medium-term scaling to the gigaton scale. Additionally, sufficient anoxic basin volume exists (>500,000 km3) to sequester climatically-relevant quantities of carbon. This is an advantage relative to terrestrial storage applications that are often limited by available volume (each gigaton of biomass has a volume of approximately 1 cubic kilometer).

Durability: Durable (>1000-year) storage of carbon is is fundamentally controlled by the fact that hypersaline waters in the basin do not mix into overlying water on short timescales; brines in the basin today have been trapped there for at least 7,900 yrs (Addy and Behrens, 1980) because excess salt creating a very strong density gradient at 2250 m depth. Due to this long residence time of brine in the basin, the water is fully anoxic, which also reduces rates of biomass breakdown. Importantly, even the fraction of the biomass carbon that is slowly respired within the brine is trapped by the lack of significant mixing between the brine and the overlying seawater. At the scale of our proposed project, effectively 100% of the biomass carbon that reaches the deep basin is trapped for at least 1,000 years.

Minimization of Ecological Risk: ABCS minimizes risks to benthic and deep-ocean animal communities by avoiding the environments in which they can live. Anoxic basins are also physically restricted, which means that any environmental impacts are localized and unable to spread over a large area. This dramatically reduces project risks relative to other pathways that operate in the open, interconnected, more physically dynamic ocean. Additionally, because microbes in this environment primarily respire sulfate, the environment will not experience major changes in oxygenation or pH, which are critical concerns in oxic systems. Finally, in contrast with CDR approaches that use marine biomass, ABCS does not significantly perturb the marine nutrient cycle. On land, approaches are well established to manage the loss of the small quantities of nutrients trapped in the biomass materials.

Affordability: To reach gigaton sequestration levels the cost per tonne of CO_2 removed must be as low as possible. Carboniferous's process has distinct price advantages over other BiCRS and CDR pathways in carbon utilization, transportation efficiency and minimal processing. High carbon efficiency is enabled by not burning the biomass. For each tonne of biomass, processes like biochar and bio oil sequestration burn off ~50% of the carbon contained in the biomass, while Carboniferous uses the biomass as a sequestration medium without "wasting" half of the carbon, nearly doubling our impact. Secondly, by using predominantly maritime transportation, the cost per tonne for transportation is also very low even over long distances. And finally, the lack of extensive processing increases affordability. Where most other BiCRS pathways need dry material, the ABCS process can utilize either wet or dry biomass which increases the types and conditions of biomass available for CDR.

Equitability: The ABCS process uses crop biomass from near the Mississippi and maritime transportation along the Mississippi river, creating jobs predominantly in rural communities. Sourcing crop wastes for sequestration generates financial opportunities for farmers and other industries in the agricultural supply chain. And, by purchasing annual crop biomass, food prices are decreased because the increased revenue to farmers acts as a food subsidy. Finally, our selection of a storage site within the U.S. EEZ but far from the coasts or any human populations avoids concentrating risks or other negative impacts in local communities.

Verifiability: Deep hypersaline anoxic basins are effectively isolated from the open, well-oxygenated ocean due to very slow mixing rates. This means that our sequestration site has boundaries to contain any breakdown products and limit the spatial area relevant for monitoring.

Our Team: Our team has extensive experience managing and building biomass processing companies, and we collaborate closely with a world-class team of researchers across multiple universities to ensure that our efforts are based on the best available science. We work with researchers at the University of California Santa Barbara to investigate breakdown processes and environmental impacts; with electrochemists at Indiana University to develop targeted in-situ sensors for in-basin research and MRV; and with with experts in agricultural biomass processes at Louisiana State University (Ag Center) to optimize our biomass processing. Scientific research results are shared openly with the scientific community (e.g., at AGU fall meeting 2022, Lower Carbon Capital MRV workshop 2023, OCB summer workshop 2023, and Raven et al., in review, preprint doi:10.22541/essoar.168276141.13056479/v1) to build credibility and engage the expertise of the larger scientific community. We are building a strong and scientifically robust foundation for our approach that will be a key advantage in earning both permit approvals and social license.

Our project addresses two of the priority innovation areas in the RFP. The first is that it is a novel approach to CDR that adapts existing industry systems for CDR. Our approach is novel because there are very few other groups looking into using anoxic zones as a way to do CDR. The second is that it is a BiCRS pathway that maximizes CDR efficiency while minimizing cost. This is because we use marine transportation, do not carburize the biomass, and have a very stable storage mechanism.

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.

Carboniferous's goal is to understand the safe biogeochemical capacity of anoxic sequestration for major anoxic basins on Earth today and, if supported by the data, gradually and responsibly increase the scale of sequestration while monitoring the environmental impacts of biomass placement in the anoxic environment.

The proposed project specifically is the placement and monitoring of a series of large burlap wrapped sugarcane bagasse "burritos" within a large anoxic basin off the coast of Louisiana. In addition to the biomass, mixing rates between the naturally occuring anoxic zone and the oxygenate ocean will be studied, along with the rate of methane consumption in the water column by Methanotrophs. A suite of sensors will be deployed to quantify the total rate of biomass breakdown, the fraction of that breakdown that was associated with methanogenesis, and how the biomass breakdown products physically mix both within the basin and with the overlying ocean.

The physical process of movement of biomass for this project is very simple. Sugarcane fiber (bagasse) is sourced from a sugarcane facility near the Mississippi river, wrapped in burlap, and tied with natural materials, creating an all natural biomass "burrito". The burritos are waterlogged and then placed onto a barge and transported to the anoxic basin where they have sensors attached and are lowered into the basin for sequestration and study.

The cost breakdown for this project is $274/tonne of CDR, with $730/tonne of MRV, for a total of $1004/tonne. As the scale of sequestration increases, the ratio of MRV cost to tonnage decreases dramatically. The second largest contributor to the high cost per tonne at this scale is the cost of barge transport, which is similarly dramatically reduced when ships are fully loaded. It is possible to sustainably source 10 million tonnes of bagasse and over 200m tonnes of corn stover per year within 30 miles of a barge loading facility on the Mississippi river.

Worldwide, approximately 3.5 Gt of grain is produced yearly (USDA WASDE-637-2). Residue ranges between 2 and 4 tonnes of dry biomass per tonne of grain production, and there is ~1.6 tonnes of CO_2e/tonne of dry biomass. Therefore there is between 11 and 22 Gt of CO_2e stabilized in grain byproducts available per year. At the scale of massive operations (0.5 Gt/yr), we would be handling between 3-6% of the grain byproduct produced yearly. Global crop residues would need to be sourced worldwide and we would need to be operating across a suite of anoxic basins, most importantly the Black Sea. At this scale, custom shipping infrastructure would be essential for maximizing efficiency.

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.

The biggest risks to this project are permitting, MRV and environmental disturbance.

Permitting: This project falls under the EPAs jurisdiction and will require an approved permit to move forward. The permit process typically takes 6 months but can take longer. We have been working to minimize this risk by communicating with EPA staff before submission and by providing a rigorous scientific basis for all aspects of our requested tonnage.

MRV: Measurement, reporting and verification in the deep ocean (>2,200 m) is intrinsically difficult and presents substantial risks for our project timeline. Primarily, we require sensors for the carbon system and other chemical species that are just now being developed and customized for our type of application. Although we have identified a promising suite of sensors that could achieve our MRV needs and are actively coordinating with vendors, there are uncertainties in the timeline for development of and access to these sensors.

Environment: Placement of biomass within the basin could enhance mixing of methane from the brine into the deep water column. Initial data show low rates of mixing and high rates of natural methane removal from the oxygenated water column and therefore indicate this is a low risk, but we will continue to study methane cycle impacts in detail during pre-deployment experiments and sequestration.

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)*	500 tonnes of CDR
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	Q4 2024
Levelized Price ($/ton CO_2)* *(This is the price per ton of your offer to us for the tonnage described above)*	$274/tonne of CDR + $730/tonne of MRV for a total of $1004/tonne

** 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]