Frontier

Carba

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

Carba

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

Minneapolis, MN

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

Andrew Jones, PhD

Brief company or organization description <20 words

Carba puts solid carbon back underground

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.

Carba removes carbon dioxide from the atmosphere and stores it deep underground in the form of a solid carbon that is permanent for thousands to millions of years. Using cutting-edge pyrolysis technology, Carba's processing units drastically speed up the natural processes that formed coal from plants hundreds of millions of years ago. These coal deposits have remained stable for 300 million years underground.

Carba's process is depicted in Figure 1. Plants breath in carbon dioxide and use solar energy to upgrade it to carbohydrates such as lignin, cellulose and hemicellulose – the structure of plants. Plants die, or are harvested, and the carbohydrates begin to degrade by microbes and fungi (or fire) releasing all the carbon back into the atmosphere as carbon dioxide (CO_2) and methane (CH_4). This inhale and exhale of CO_2 by plants occurs in year-long or decade-long timeframes and creates the so-called 'fast carbon cycle.' Carba breaks the cycle at this critical moment by transforming dead biomass into solid carbon through a low-temperature pyrolysis process. This process transforms the carbohydrates, which are food for microbes and fungi, into highly aromatic unsaturated carbon moieties. This solid carbon is then buried underground below the anoxic layer to protect the carbon from degradation mechanisms present at the surface. In the absence of burial, even highly aromatic graphite, coal and activated carbons can be degraded by microbial and fungal attack, mechanical attrition and dust formation, photo-oxidation, ozone/chemical oxidation, freeze/thaw cycling, runoff, infiltration and more. Anoxic burial is an effective solution to prevent degradation as evidenced by the 300 million year old coal seams naturally found around the globe.

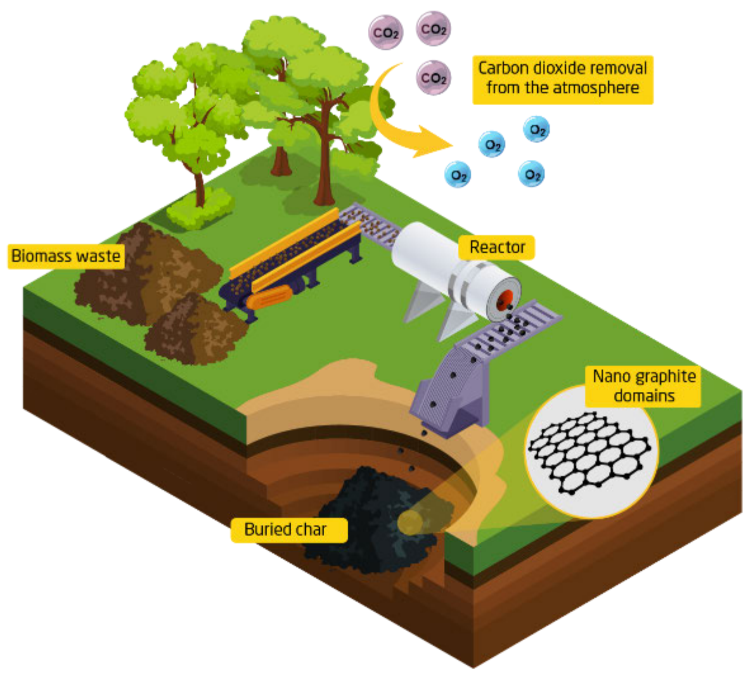


Figure 1. Schematic of Carba's CDR solution

What makes Carba unique is its proprietary reactors that lead to the highest possible carbon yields in the shortest amount of time. This translates into lower cost, lower energy, and better biomass utilization. Higher temperatures, and/or other reactor designs, lead to carbon cracking reactions that can generate toxic bio-oils and vapors, and reduce carbon yields. In addition, Carba's patent-pending process includes the burial of carbon underground below the anoxic layer. This allows Carba to bury in almost any location with certain precautions. Decentralized burial combined with decentralized portable reactors reduces transportation costs and energy utilization. Taken together, Carba's CDR solution promises the lowest cost and lowest energy approach to permanent carbon dioxide removal.

Carba's approach differs from centralized industrial-scale carbon capture facilities. Instead, we rely on the direct air capture machines provided by nature – plants! Plants have perfected the process of carbon removal, they self-replicate, run on renewable solar energy, grow without human intervention, and they are beautiful! But utilizing biomass comes with it own set of challenges. These include scale, decentralization, and land use.

Scale:

Is there enough biomass? Estimates of biomass waste produced around the world range from 10-140 billion tons per year, with our best estimate sitting around 40 billion tons per year. With Carba's process, this could lead to up to 32 billion tons of CO_2e permanently removed per year, which is more than enough to solve the negative emissions climate problem. Furthermore, since these biomass waste streams are inevitably degraded back to CO_2 and CH_4, the solution is completely additional. In most cases, the counterfactual involves piles of biomass waste composted, burned or spread back into fields to decompose. In any case, all the carbon is re-released as carbon dioxide and methane in several months or years.

Decentralization:

How do we access and process a waste stream that is decentralized around the world? Carba solves the two main issues of processing an inherently decentralized resource. First, Carba's reactors are portable and self-powered (once started). Second, burial is also decentralized and doesn't rely on centralized injection sites, pipelines or complex transportation networks. Carba utilizes the large network of abandoned mines and quarries for large scale burial. This has the benefit of remediating the land and avoids the need for digging a hole. We are also pursuing burial in landfills as an alternative daily cover where the high surface area of the carbon promises to adsorb toxins such as PFAS and mercury, reduce odors, and reduce methane production in the landfill. The solid carbon is inert, organic and doesn't require special permitting for burial. No special requirements, such as plastic liners or encapsulation are required. Burial has the additional benefit of improving verifiability/MRV because the solid carbon is contained in a relatively small area, can be monitored, and can be analyzed to assess permanence.

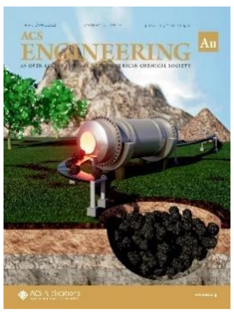
Land use:

How much land will this use and will it lead to leakage? A network of thousands of processors will be required to reach gigatonne levels of CDR, however, the footprint of these processors is relatively small, around 20' x 20'. The processors live on portable trailers and are ideally located at the site of biomass waste production or aggregation. The additional land use is, therefore, marginal. Carba only sources waste biomass that would otherwise be burned or composted, and is of low or no value. There is no incentive for producers of this waste to use more land to make more waste.

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.

Carba is building a commercial scale portable carbon dioxide removal facility in Burnsville, MN. The reactor will be situated on Waste Management property between the sanitary landfill and a compost facility that aggregates a large amount of waste from the Twin Cities metro. The fully burdened cost is around $396 per tonne CO_2e not including SG&A. The bulk of this cost is labor due to the low quantity of removal with a single reactor and the need for redundancy in operators 24/7 at this stage. We expect this cost to come down appreciably with more reactors and automation. Our goal is to have three reactors running on site, and with additional automation we project that should bring our costs down below $100/t. A more detailed LCA and TEA of our process including a Monte Carlo analysis that accounts for the variability of input variables is published in the ACS article Overcoming the Entropy Penalty of Direct Air Capture for Efficient Gigatonne Removal of Carbon Dioxide | ACS Engineering Au.

Scaling to 0.5Gt removal will require a network of processing sites around the globe. Carba targets



sites with biomass waste aggregation >40,000 tons/year. At this scale, around 12k sites will be required. Carba will maintain these sites with a network of system operators and a fleet of maintenance crews. The portable and modular design of the reactors allows them to be easily changed, added, or removed for maintenance or in response to feedstock supply changes. The reactors can process a wide variety of feedstocks and are produced in-house at scale.

Quantification of the carbon removed involves (gravimetrically) weighing the solid carbon produced and subsequent analysis of the carbon content. For example, a pile of solid carbon may be loaded into a temporary dumpster and weighed using a truck scale (on-site at Waste Management). A sample of the carbon is analyzed for CHNS content using a lab-grade elemental analyzer such as the Elementar EL Cube. Oxygen content is ideally determined using the direct method to avoid errors with the difference method, but is not required for carbon content determination. The elemental analyzer works by burning the sample in the presence of oxygen and then measuring the products (CO_2, H_2O, NO_2, etc.). The products are separated with a gas chromatograph column (e.g., Plot Q) and measured with a thermal conductivity, and/or infrared detector. If the mass of solid carbon is 1000 kg and the carbon content is 76%, then the total carbon removed is 760 kg, with a carbon dioxide equivalence of 760 * 44/12 = 2787 kg CO_2e. In general, burial sites will be monitored for reversal (e.g., degradation of the solid carbon) by measuring CO_2 and/or CH_4 emissions at the burial site. Although we do not expect any reversal, if reversal occurs, it will be subtracted from the total carbon removed. Landfills present additional challenges in measuring gaseous degradation products due to the high background of methane production, which is subsequently flared at this site. In this case, solid carbon samples will be buried and excavated after one year to determine if any reversal occurred. Additional diesel or fossil fuel usage will be accounted for and subtracted from the carbon removed on an appropriate basis.

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 the economics of the project are the rising costs of biomass waste and transportation costs. We mitigate the risks of high transportation costs by co-locating where biomass waste is already aggregated and/or produced. Transportation after conversion is cheaper because the solid carbon is a third the weight and occupies less volume. Ideally, this location is also close to the burial site. Carba's portable reactors and decentralized burial help ensure these costs and the energy requirements of transportation are low. Biomass waste costs will increase as the demand for biomass waste increases. This will lead to increasing prices over time for all biomass utilization projects and a competition for these resources. These risks can be mitigated through strategic partnerships and flexibility to access more locations and types of waste. Biomass utilization projects have a storied history. The high-profile failures of KiOR, Ineos, Range Fuels and others have taught us lessons about what not to do and how to avoid the pitfalls involved with biomass utilization. Nonetheless, there are technical risks in the scale-up of any biomass utilization projects. Specifically, there are risks that biomass variability in size/shape/composition and the presence of foreign materials (e.g., metal) could cause problems during operation. Carba's team has decades of experience in bulk material handling of biomass waste, and we have designed the reactor with conservative safety factors to ensure these issues do not cause unnecessary downtime. There are market risks in the adoption of this novel method. Adoption of this method by Frontier and other leaders in CDR will help mitigate this risk. Financial risks include the ability to raise debt or equity financing to scale to meet climate goals. Offtake and pre-purchase agreements can help mitigate these risks. Lastly, there are risks in landfill burial that organic material in landfill leachate could stimulate methanogenesis of the carbon. To mitigate for this risk, we will be testing samples one year apart by taking core samples in real-world landfill settings to measure any potential degradation of the samples. In parallel, we are working with NREL on a DOE grant, the Yale Carbon Containment lab, and other leading scientists to further study permanence in different below ground environments.

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)*	1,111 (with a 10% discount, we will actually be producing and storing 1,234). Note that we are open to selling more, but have capped it at $500k per the RFP.
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	February 2025
Levelized Price ($/ton CO_2)* *(This is the price per ton of your offer to us for the tonnage described above)*	450

** 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).*