Frontier

Karbonetiq, 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

Karbonetiq, Inc.

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

824 E Haley Street, Santa Barbara, CA 93103

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

Dr. Michael Wyrsta
Dr. Mark Tilley

Brief company or organization description <20 words

Karbonetiq is pioneering low-cost carbon removal through innovative direct air mineralization (DAM) of reactive industrial waste.

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

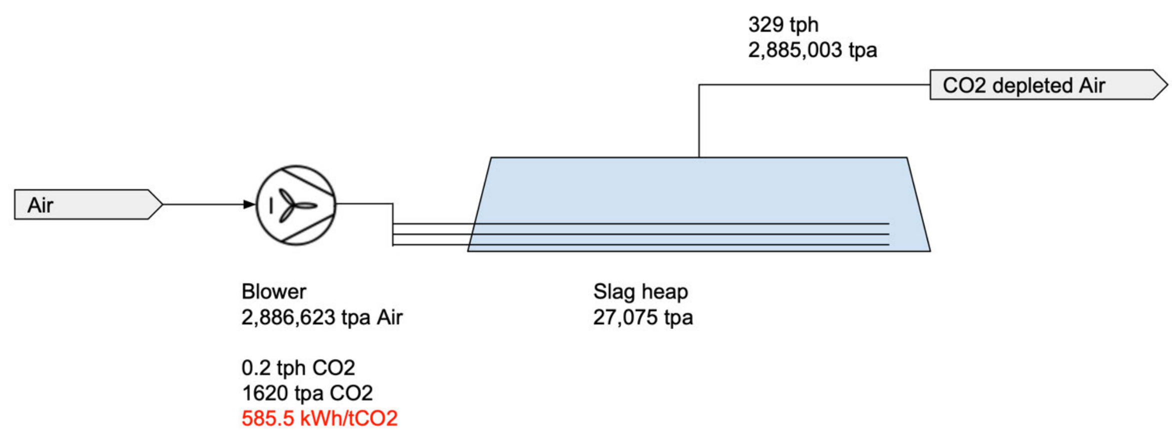
a. **Description of the CDR approach:** Describe how the proposed technology removes CO_2 from the atmosphere, including how the carbon is stored for > 1,000 years. Tell us why your system is best-in-class, and how you're differentiated from any other organization working on a similar approach. If

[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.

Karbonetiq's CDR approach uses direct air mineralization and reactive waste minerals to create geologically stable mineral carbonates. Specifically, Karbonetiq will use designed low-cost heap piles of industrial waste minerals with **passive and forced** air transport through those piles to trap CO_2 from the air as mineral carbonates. We are explicitly addressing Frontier's Innovation focus areas: **Approaches to geochemical CDR that accelerate weathering rates** and **New DAC approaches that enable dramatic cost reductions.** We use co-generated waste minerals that are thermodynamically primed to react with CO_2 from the atmosphere on a large site already powered entirely by renewable energy. Our approach of using minerals on a single-use basis eliminates the requirement to expend a large amount of energy to recycle and reuse the minerals. This results in much lower CAPEX and OPEX in comparison to conventional DAC approaches. We believe we can achieve the long-term cost target of <$100/t CDR.

Figure 1. Basic process flow and overall mass balance. Structured piles of reactive waste minerals react directly with air to form stable carbonates.



Thermodynamically primed minerals (TPM) are industrial waste minerals that have been thermally processed. Examples of TPM and their respective associated product: steel slag from steel production; petcoke ash from steam production, GOB ash from GOB waste pile cleanup, cement kiln dust from cement manufacturing, carbide lime from acetylene production; coal ash from power production; scrubber sludge from acid gas management; and lime fines from calcium and dolime production. There are some waste rock and mine tailings that could be classified as TPM as well.

The key reaction, in idealized form: $Ca(OH)_{2(s)} + CO_{2(g)} \rightarrow CaCO_{3(s)} + H_2O_{(l)}$ $\Delta H = -112.33$ kJ/mol

This reaction is thermodynamically favorable and is representative of the chemistry happening in the slag pile as we push air across its surface. Many metals can form similar stable carbonates besides calcium, along with more complicated mixed metal carbonates. Mineral carbonates such as calcium and magnesium carbonates are chemically stable for more than 1000 years, making them ideal candidates for CDR applications.

Historically, large mineral waste piles have been managed to maximize volumetric storage or, in some cases, landfilled unintentionally, significantly reducing the piles' ability to react with atmospheric carbon. We intend to actively design and manage these piles to maximize their CO_2 mineralization potential. We recognize the importance of a "light touch" approach when sequestering carbon dioxide cost-effectively. That is why we have focused on TPM and pile design along with **active and passive** airflow. Karbonetiq is developing methods to enhance airflow across and through slag piles using both **passive and active** methods. This addresses two priority innovation areas identified by Frontier, **Approaches to geochemical CDR that accelerate weathering rates** and **New DAC approaches that enable dramatic cost reductions.**

There are billions of tons of these TPM being produced every year, and many billions of tons of legacy material are in every major economy of the world. For example, over 600 million tons of steel/iron slag is produced every year with an estimated gross CO_2 mineralization potential of approximately 268 million tons per year. Legacy slag has the potential to mineralize 8.2 $GtCO_2$. Compiling other TPM legacy sites, and other fresh reactive mineral waste production sites, we anticipate >500 million tons of CO_2/year mineralization potential.

Ref https://doi.org/10.1016/j.ijggc.2019.05.021

Best In Class

Team

Our proposed single-step complete CDR system is best in class for several reasons. The principle Karbonetiq team has been working with CO_2 mineralization and other mineral systems for over a decade and have direct experience with heavy mineral industry leaders. Karbonetiq founders and team members have developed cutting edge mineral processing chemistry and process for a variety of mineral targets and therefore are uniquely positioned to assess the difficult task of direct air mineralization. Karbonetiq team members have >60 unique patents/applications mostly focused inorganic/organic processing and hydrometallurgy. Karbonetiq founders and team members have also developed fast and simple methods to rapidly measure mineralization potential of prospective mineral sources so that we can accurately assess a sites CDR capacity.

Experience

Our team has conceived, designed and deployed several technologies over our professional careers. We have detailed knowledge of the types of sites, the companies that own them, the management teams and unique corporate culture required to navigate the planning and deployment of a new technology on a site. The Karbonetiq team knows many people in the mineral industry and have nurtured relationships over the years to get us quick impactful access to company leaders.

The team has also developed a healthy appreciation for logistics and how they directly impact the economics of a project involving low-value industrial minerals. Karbonetiq is also connected to the EPC community and has extensive experience working with engineering firms which gives us insight into deployment scale-up, timing and the associated costs with both process engineering design and civil engineering efforts. We have also cultivated many relationships with equipment vendors and know how to work with them to get the best pricing and timing of requested equipment or supplies.

We have invented and/or brought to market or piloted the following:

Recycled steel slag and conversion to a product for sulfur capture technology; Methane bromination to fuels technology; Hydromet process and chemistry for slag to precipitated calcium carbonate; Inorganic low-k dielectric materials for ICs; Oxidative coupling of methane to olefins project; Frac water processing and cleanup process; and others.

Our experience has enabled us to quickly identify, and initiate partnership discussions with resource owner management teams of very large TPM piles. These piles have no economic value, retained significant reactivity and are in places that have near total renewable energy already in place, and abundant non-arable industrial land.

Site

This initial project site is best in class for several reasons. First the site is large in volume and reactivity. The project site has an available slag inventory of over 50 million tons, and a reactivity of at least 60 kgs of CO_2 per ton of slag processed. The size of the site is a differentiator because it enables us to develop long-term plans, gain operational experience and foster best practices for handling and carbonating similar materials.

The second is that power generation feeding the site is 100% renewable, enabling high net CO_2 sequestration.

Technology

Our technology is best in class because we have the lowest cost approach to direct air mineralization. We have achieved this by not only targeting single use materials, but also by applying over a decade of learning and design of hydromet and mineralization technologies to design our engineering system. In the lab we have carbonated 100's of different kinds of TPM from all over the world with varying reactivities. We have tested steel slags, lime waste from kiln operations, carbide lime, petcoke ash, waste-to-energy municipal ash, coal ash, GOB ash, copper tailings, smelter waste, cobalt tailings, low-grade lime, and others. Based on our analysis a gigaton scale CO_2 sequestration technology cannot use any added liquid chemical system that requires recycle and reuse. The associated losses on solids/liquids handling, make-up, capex, energy, fouling etc…are too great to overcome and hit $100/t CO_2 sequestration targets. This is why we designed the lowest cost system with reactive minerals using modular, scalable, mobile, equipment allowing for eventual land reclamation activities. We have recently begun work on new TPM pile design to enhance both **active and passive** airflow across and through the piles.

The first phase demonstration-scale project aims to remove and permanently store **1588 Tons/yr** of Carbon Dioxide and will be in place and running in Q2/3 of 2024 with an expected operating time span of 1 year. We expect this to be a feasible scale for us to execute. The pile size is 50 m by 50 m by 2 m in size and would be changed out and replenished quarterly.

The second phase, beyond the scope of this project, is to investigate the feasibility of grinding slag, the impact on cost, energy consumption and total net CO_2 captured. Our initial lab results show a 2x improvement in CO_2 mineralization when ground slag is used. However, there are other issues to contend with including pressure drop when using fines, dust generation, fines handling and increased labor requirements. We will also investigate the use of blended lime waste, currently on site in large volume (>1 million tons), with slag to enhance the volumetric capacity of the piles. Our initial lab results show that our partners lime waste is 4x greater in CO_2 capture per unit mass than the slag we plan to use.

Other

We have recently signed a letter of intent to begin design of a coal waste ash mineralization project in the US with a gross CO_2 mineralization potential of 120,000 tons per year. This will further enhance our capabilities and leverage our relationships to help deploy our technology for this project.

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.

Overview of Objectives

We are trying to build a cost-effective, scalable direct air mineralization process and pile design that can be easily monitored and verified, and moved from site to site once the reactive minerals are consumed. The first phase demonstration-scale project aims to remove and permanently store a net **1588 Tons/yr** of Carbon Dioxide.

TPMs are often piled up on the production site on land that is not used for anything but piling waste. These sites include facilities actively producing waste minerals, mothballed or abandoned sites, tailing ponds, and dedicated landfills. Specifically, the site for this project is a Canadian steel mill with over 1600 acres already dedicated to slag storage and management. The site has been piling slag waste for over 100 years. We estimate approximately 50 million tons of reactive material are located at this site, with another 750,000 tons per year being added to the site. The carbon mineralization potential for this site is estimated to be up to 3,000,0000 tons of CO_2, using unground legacy slag, and 6,000,000 tons of CO_2 mineralization potential if a grinding circuit were to be used. The ongoing fresh slag additions to the site are estimated to yield annually between 60,000-112,500 tons of CO_2 mineralization potential.

We have partnered with the site owner to deploy our first demonstration-scale pilot, with the aim of carbonating 27,000 tons of slag, annually for two years, with a net sequestration of 1588 tons of CO_2 per year. A 500,000-ton pile carbonation pile will follow the successful completion of this demonstration and then, and then eventually at full-scale, an annual 5,000,000 ton pile carbonation process. Although this scaling uptick may seem large there is little risk in making the pile larger from a scaling perspective. We will follow well-tread airflow design practices to make sure we are actively aerating the pile. The scaling of the blowers is primarily linear up to 300,000 cfm. There may be some opportunity to go even bigger however our plans are to deploy sequential units, eliminating any scaling risk for blower deployment.

Figure 2. A fraction of the slag at the site is pictured here. Note the stacking height, >200 ft. Our ultimate goal is to design efficient air transport through piles of this size to mineralize sizable quantities of CO_2.

Specific Cost Breakdown

Our capital cost is driven by two main pieces of equipment: the blower and the piping network. These two components represent 57% of the Total Bare Erected Cost. The next largest line item is the associated labor, and equipment rental to construct the piles representing 31% of the Total Bare Erected Cost. Optional equipment like a grinding circuit has been left out of this analysis because of the high initial capital outlay. Our overall approach is to have very limited solids handling. This saves us labor costs and emissions from machine use.

Reaching $100/t

Based on our initial TEA of this project our total levelized cost of net CO_2 removed is \$103/tCO_2, which is very close to achieving Frontier's $100/t target. We believe further cost reductions can be realized as the technology and deployment mature. Larger-scale operations will capture savings on capital equipment purchases, better pile design to take advantage of passive air movement will reduce some of the need for blowers, and operational experience will lower the fixed operational costs, including maintenance costs (this is an ongoing and active IP generation campaign).

And 0.5 Gt/yr

Meyers et al, estimate 268 MtCO_2 could be mineralized per year using slag from steel operations and another 8.2 GtCO_2 from legacy slag piles. https://doi.org/10.1016/j.ijggc.2019.05.021 According to the USGS the yearly global production rate of waste rock is 72 billion tons, with an additional 8.85 billion tons of tailings. Current global tailings piles are estimated to have 282.5 billion tons of tailings. This implies that there are over 2.3 trillion tons of waste rock potentially available to sequester carbon. These resources plus industrial mineral waste represent a large opportunity to carbonate well over 0.5 Gt of CO_2 per year. Our goal is to develop the technology to mitigate the energy cost needed to effectively use these minerals.

Ref. TOWARDS ZERO HARM – A COMPENDIUM OF PAPERS PREPARED FOR THE GLOBAL TAILINGS REVIEW

Quantifying Carbon Removal

Verifying carbon mineralized will be done using before and after sampling of the pile. Samples will be taken from a variety of pile positions and depths. Positions will be marked for follow up testing to monitor pile carbonation. Samples obtained will be ground and sieved and then immediately tested via quant XRD for mineralogical phase identification and quantification and simultaneously tested on a TGA-MS to get quantitative CO_2 yield. Time varied sampling and analysis will give us a clear picture of the rate and degree of carbonation of the pile along with spatial data giving us insight into pile design. Future designs may include loadcell design and strategic placement under the pile to enable real-time mass changes across the pile, thereby getting us implied carbonation rates and mass accumulated.

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 Risk

The biggest technical risk is the rate of carbonation/utilization using air. This is directly related to the cost per ton of CO_2 removed from the atmosphere. The best way to mitigate this risk is by designing and integrating new pile layouts to take advantage of passive airflow. The more we can use natural airflow to carbonate the pile, the less energy we will need to push air through or across the pile forcefully.

Another technical risk is the pressure drop through the pile and ensuring good airflow distribution. This will be addressed by pile design, particle size choice, layering design and ultimately blower choice. Since the pile is reactive and exposed to the elements, we expect to see changing conditions as the pile ages. We will try to anticipate these changes, like slag expansion, and mitigate those early in the design process.

Project Execution

Inability to staff, partner back out, equipment shortages, permitting challenges, local community push back are all execution risks that will need to be closely monitored and addressed early.

MRV

Inconsistent data, poor sampling procedures, could lead to erroneous assumptions about the pile's level of carbonation. We will prevent this from happening by designing and implementing rigorous procedures and processes that field technicians will utilize to acquire samples and the relevant data.

Ecosystem

The largest risk is mostly likely dust control. The site currently uses dust control agents to suppress dust migration into nearby ecosystems and communities. To mitigate any dust issues with our process we could use reusable geotextiles to cover the piles, allowing for air and water to pass through but retaining a large component of any dust released from the slag.

Financial

The primary financial risk for the project proposal would be reduced capacity (of carbon sequestration) due to the technical risk described in the first paragraph of this section. In addition, cost over-runs in the EPC budget are also a potential risk. Changes in the regulatory and policy environment could also influence the financials of the project: carbon pricing mechanisms, emission reduction targets, government incentives and subsidies could all change. Meeting our schedule for the project is also a factor, and we recognize we will need the continued support of the steel mill team to achieve our timeline.

d. **Proposed offer to Frontier:** Please list the 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)*	3176
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	Q2/3 2026
Levelized Price ($/ton CO_2)* *(This is the price per ton of your offer to us for the tonnage described above)*	157.43

** 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]