Karbonetiq, Inc.

Carbon dioxide removal prepurchase application

Summer 2024

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 2024 summer purchase cycle. Include as much detail as possible but omit sensitive and proprietary information.

Company or organization name

Karbonetiq, Inc.

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

819 Reddick 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 passive 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 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. 1000-1500 words

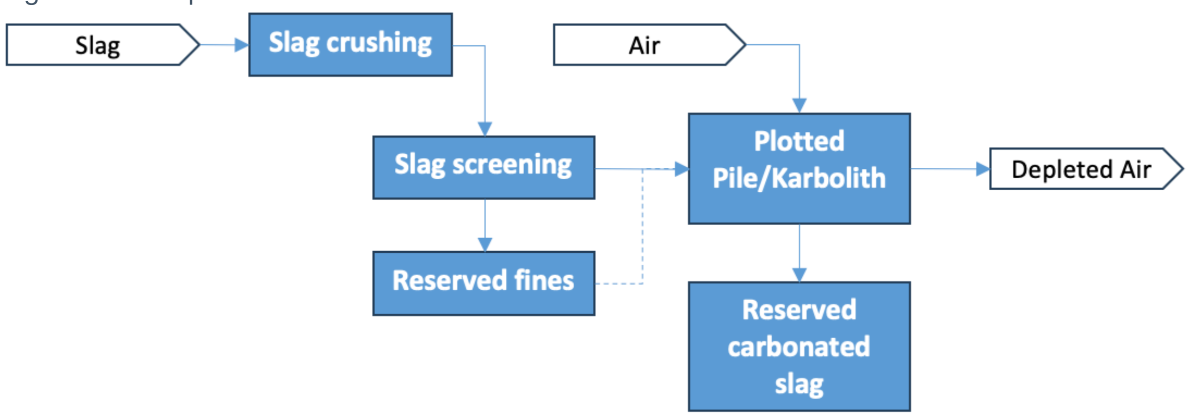
Karbonetiq's CDR approach uses a power-free air-transport and reactive waste minerals to create geologically stable mineral carbonates. Specifically, Karbonetiq uses low-cost piles of industrial

[1] We use "project" throughout this template, but the 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.

waste minerals with a **passive air transport device (the Karbolith)** to trap CO_2 from the air as mineral carbonates. We are explicitly addressing Frontier's Innovation focus areas: **Alkaline Feedstocks.** We use co-generated waste minerals that are thermodynamically primed to react with CO_2 from the atmosphere on the site of their generation. 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.

Our system is best-in-class because: We don't need electricity to run our process; We use nature to move air; Our system is very low cost; The resulting CDR is stable and directly measurable.

Figure 1. Basic process flow.



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** (the TPM for this project); 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 air moves through the pile. 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.

Figure 2. A drone shot of our commercial-scale demo operating at our partner site in Pennsylvania, USA. We call the unit the Karbolith. The derives from the company name + lith (lithos for rock and monolith as a ref to 2001 Space Odyssey).

Historically, large mineral waste piles have been managed to maximize volumetric storage or, in some cases, landfilled, significantly reducing the piles' ability to react with atmospheric carbon. Karbonetiq has designed, built and deployed a commercial-scale demonstration unit at a partner site in the US. We intend to launch our new, but largely similar, design, at our partner steel mill to mineralize atmospheric CO_2 on their legacy slag piles. We recognize the importance of a "light touch" approach when sequestering carbon dioxide cost-effectively. That is why we have focused on TPM, passive air transport, logistics and pile design. Karbonetiq has developed methods to enhance airflow across and through slag piles using **passive** methods.

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. 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 experience developing cutting edge mineral processing chemistry and processes 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 experience developing 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.

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 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 an upper-bound reactivity of 180 kgs of CO_2 per ton of slag. 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 the site is large, 1600 acres. This gives us ample room to deploy our technology and process large volumes of material. An additional advantage, to the extent if we need it, of the site is that power generation feeding the site is 100% renewable.

There are thousands of sites like these around the world with ample fresh/legacy material available to mineralize ~0.5-1 Gt of CO2 per year.

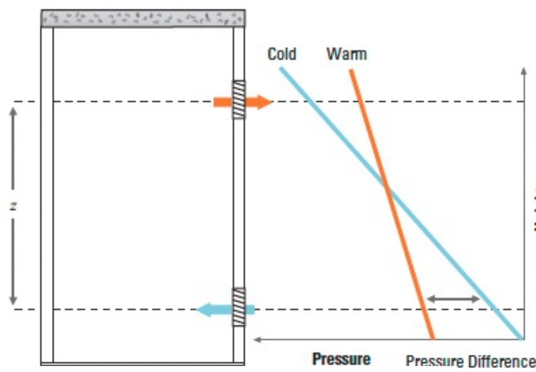
Technology

Our technology is best in class because we have the lowest cost approach to direct air mineralization. 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. Our approach is based on fundamental physics of moving air, highlighted by our experience with reactive solids handling, carbonation and validation.

The first phase demonstration-scale project aims to remove and permanently mineralize a net **2958 Tons/yr** of Carbon Dioxide and will be in place and running in Q4 of 2024 with an expected operating time span of 1 year (just a project definition we intend to keep running the unit and add more units to the site over the course of several years). We expect this to be a feasible scale for us to execute. The demo footprint is 50 m by 50 m in size.

Figure 3. Inspiration and basic physics. Panel A shows wind-catchers used to passively transport air through buildings in hot and arid climates. This has been used since antiquity. Panel B describes the basics physics behind buoyancy-stack effect driven airflow and is a staple in commercial building design.

A



B

$$\Delta p_{inlet} + \Delta p_{outlet} = \Delta p_s = (\rho_{outside} - \rho_{inside}) g \Delta z$$

Where:
p = the pressure in lb/ft² or Pa
ρ = the fluid density in lb/ft³ or kg/m³
g = the gravitational acceleration, 32.2ft/s² or 9.81m/s²
z = the difference in height between two points in ft or m

Price Engineering Guide Natural Ventilation

The second phase, beyond the scope of this project, is to rapidly expand our deployment to 1,000,000 tons of annual net CDR by 2030.

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 cost and scale criteria?[2] What is your approach to quantifying the carbon removed? Please include figures and system schematics and be specific, but concise. 1000-1500 words

[2] We're looking for approaches that can reach climate-relevant scale (about 0.5 Gt CDR/year at \$100/ton). We will consider approaches that don't quite meet this bar if they perform well against our other criteria, can enable the removal of hundreds of millions of tons, are otherwise compelling enough to be part of the global portfolio of climate solutions.

Overview of Objectives

We are trying to build a cost-effective, scalable direct air mineralization process using passive air transport 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 **2958 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 upper bound carbon mineralization potential for this site is estimated to be 9,000,0000 tons of CO_2, using legacy slag, and 4,000,000-5,000,000 tons of CO_2 mineralization potential if a crushing and screening circuit were to be used. The ongoing fresh slag additions to the site are estimated to yield annually 60,000-75,000 tons of CO_2 mineralization potential.

Our first demonstration-scale pilot has aims of carbonating ~40,000 tons of slag within twelve months of full operation, with a net mineralization of 2958 tons of CO_2 per year. After 12 months of piloting Karbonetiq plans to rapidly expand. The first expansion will be to grow to ~30,000 tpa of CDR by building and placing 9 additional Karbolith units. Within 24 months of pilot demonstration Karbonetiq plans to expand the site to 30 total Karboliths representing 90,000 tpa CDR. Eventually at full-scale, an annual 300,000 tpa CDR using 100 Karboliths. Although this scaling uptick may seem large there is little risk in scaling since the modular unit is the Karbolith and no additional scaling of the unit is required.

Figure 4. 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

Based on our previous builds we expect our delivered and installed Karbolith, including EPC costs to be <$250,000. Our capital cost is driven by two main pieces of equipment: shipping containers and the piping network. These two components represent ~50% of the Total Bare Erected Cost.

Reaching $100/t

Based on our initial TEA of this project our total levelized cost of net CO_2 removed is $58/t$CO_2$, which achieves 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 and fabrication costs, and operational experience will lower our operating costs.

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. **These minerals are often located in remote areas that do not have access to power making them ideal candidates for the Karbolith technology.**

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. CO_2 flux measurements across the entire site will be done using a Li-Cor Eddy Covariance system to give us real-time analytics and help us decide what are the best time points for pile removal. 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. 500-1000 words

Technical Risk

The biggest technical risk is the rate of carbonation. 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. However, given the low-cost nature of our approach even a 3x increase in the time it takes to reach favorable carbonation we are still below $200/ton CDR cost.

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, and slag layering design. 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, 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, however we think this will be minimal since we have already built two units. 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 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)*	2958 tpa, [expanding to 300,000 tpa at full scale]
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	December 2025
Levelized cost ($/ton CO_2) *(This is the cost per ton for the project tonnage described above, and should match 6d)*	58
Levelized price ($/ton CO_2)[3] *(This is the price per ton of your offer to us for the tonnage described above)*	170

[3] 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).