Alkali Earth

Carbon dioxide removal prepurchase application

Summer 2023

General Application

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

Alkali Earth

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

Northfield, Minnesota (USA)

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

Dan Maxbauer & Sean McCauley

Brief company or organization description <20 words

Alkali Earth repurposes alkaline minerals generated during steel production to enhance mineral weathering and mineralization of CO_2 to deliver permanent carbon removal.

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.

[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.

How we remove carbon: At Alkali Earth, we optimize the deployment of slag-based alkaline aggregate products in gravel road construction to convert atmospheric CO_2 into stable carbonate minerals, delivering permanent and verifiable carbon dioxide removal (CDR; see Fig. 1). Our materials are highly reactive with CO_2 due to their high concentration of Ca and Mg-rich silicate, glass, and hydroxide mineral phases. Crushing these materials and spreading them on road surfaces is an ideal use case for slag aggregates due to the high exposure to atmospheric CO_2 and the continual disturbance from tires that break up surface crusts to facilitate continued CDR.

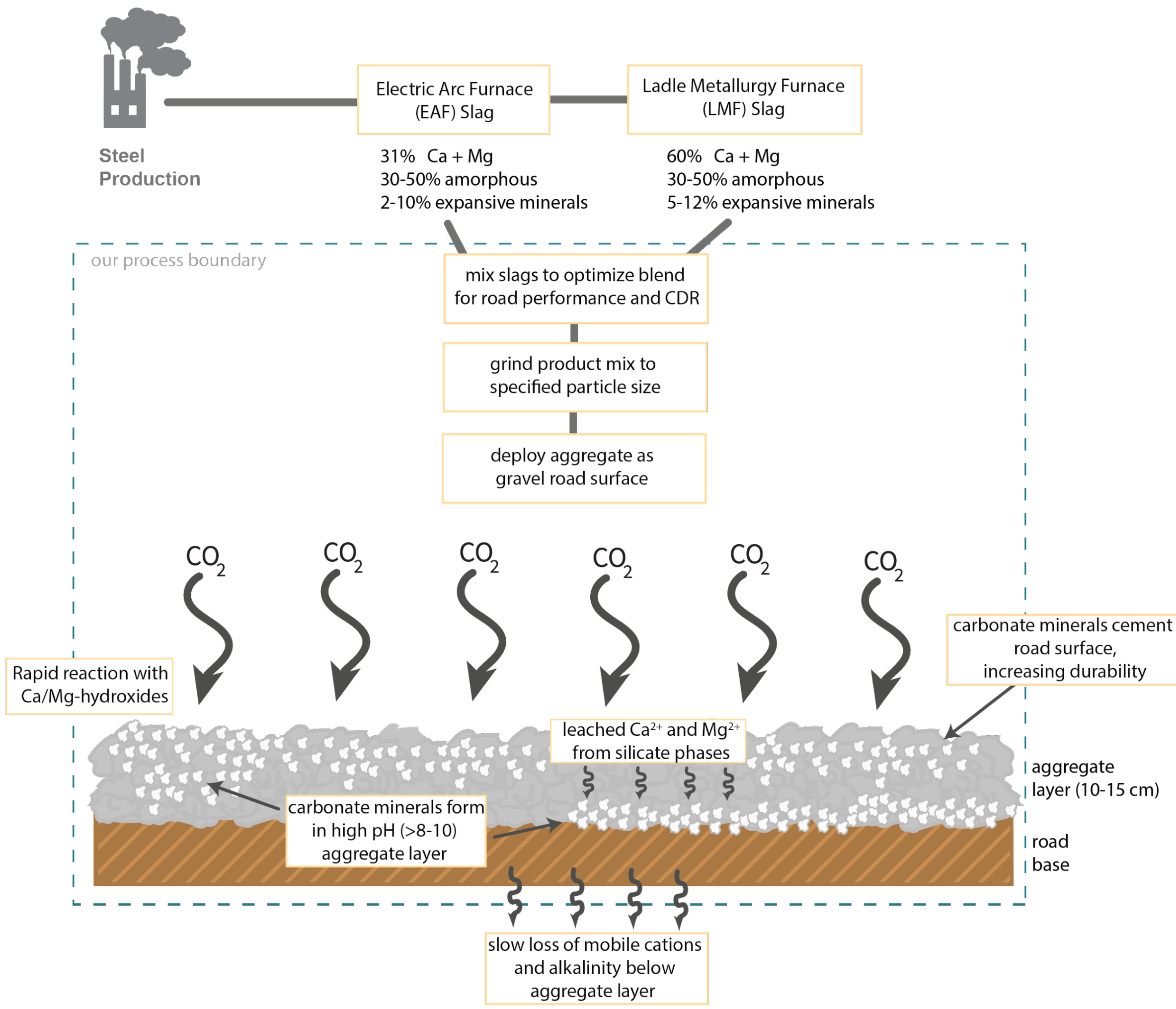

Fig. 1 A conceptual diagram showing how our blended slag aggregate products remove CO_2 from the atmosphere and our process boundaries. Carbonate minerals (shown as white minerals in aggregate layer) is the permanent storage mechanism for CO_2 in our projects. Note: expansive minerals refers to the combination of MgO (periclase), $Mg(OH)_2$ (brucite), CaO (lime), and $Ca(OH)_2$ (portlandite) in slag.

Below, we illustrate how CO_2 removal is achieved through a sequence of representative reactions using $Ca(OH)_2$ (portlandite) and Ca_2SiO_4 (larnite), both of which are present in our products:

$$Ca(OH)_2 + 2CO_2 \square Ca^{2+} + 2HCO_3^- \qquad \text{(rxn 1)}$$

$$Ca_2SiO_4 + 4CO_2 + 4H_2O \square 2Ca^{2+} + 4HCO_3^- + H_4SiO_4 \qquad \text{(rxn 2)}$$

Both rxn 1 and rxn 2 show dissolution of Ca-bearing minerals creating a buffered solution rich in Ca^{2+} ions (note we use Ca here, but our products also contain Mg-bearing mineral phases that behave similarly). Our aggregate products have high pH (~11.5), and solution chemistry in the road aggregate layer pushes equilibrium of the carbonate system towards the right in the set of reactions below (rxn 3):

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^{+} + HCO_3^{-} \leftrightarrow 2H^{+} + CO_3^{2-} \qquad \text{(rxn 3)}$$

The high pH solutions readily precipitate carbonate minerals that form in-situ within our road base (see Fig. 1 for example images) according to the equations:

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \qquad \text{(rxn 4)}$$

We note here that solid $CaCO_3$ produced in rxn 4 represents stable CDR in our roads. As our roads age, the carbonate mineral content of the aggregate increases as minerals are dissolved temporarily in reactions with acidic rainwater (pH ~5.6) that leach Ca^{2+} and Mg^{2+} into deeper layers (~10-15 cm) where additional carbonate minerals form a hard, well-cemented layer that helps to solidify the road, creating a durable surface that can last for decades (see example images in Fig. 2).

Fig. 2. Example images showing raw slag piles at production site (upper left) where exposure to CO_2 is limited within the pile, an example of a typical gravel road surface (lower panel) where CO_2 exposure is increased, and a cross section view showing carbonated aggregate cementing with carbonate minerals (upper right) after 1 year of deployment. Note in the upper right panel the white color is indicative of carbonate minerals.

How durable is our carbon removal: The end product of our CDR process are stable carbonate minerals which are verifiable within a year and that permanently store CO_2 for 1000 years or beyond in surface environments[1]. Additionally, weathering of our aggregate over several decades to centuries will break down the larger and slower reacting silicate phases. The weathering of silicate minerals is a well-known mechanism for carbon removal[2] and will likely lead to additional CDR, however we are not including this CDR in our pre-purchase.

What differentiates us:

- Our materials: We source alkaline industrial minerals that historically were landfilled or applied in low-mineralization use cases (such as construction fill) and optimize their application for carbon removal.

- Our process: We enhance weathering and mineralization in gravel roads, which we believe represents a new use-case for carbon mineralization and weathering alongside agricultural ERW, mine tailings mineralization, and carbonated construction aggregates.
- Our ability to scale: We have a long-term (3-year) project development agreement with a major international steel slag supplier that will allow us to reach scale (>1 million tons of aggregate deployed annually) on a relatively short timescale (~5 years).
- Our MRV: Perhaps most importantly, fast reaction rates and the in-situ removal of CO_2 simplifies MRV, ensuring that we can conservatively verify all of the carbon removal we claim in our projects.
- Our co-benefits: Gravel roads are everywhere and take significant energy inputs to maintain each year. Our products deliver more durable gravel road surfaces that can last decades rather than years and have reduced dust due to the self-cementing nature of our material. Our products also substitute for natural aggregates that often come from quarrying operations, so recycling pre-existing materials for this application at scale will reduce the need for mining.

Why we are what Frontier is looking for: We are working with a leader in the steel waste management industry to leverage a novel source of alkalinity by blending multiple feedstocks of alkaline minerals from steel production into valuable co-products that deliver both durable and verifiable carbon removal, along with co-benefits to the end-user.

We intend to use a significant share of the carbon removal credits generated in our projects to directly subsidize transportation costs, which currently limit the market for these materials. Decreasing the cost of transport will allow us to double the viable transportation distance, expanding the deployment area around each production facility by 4x.

We recently executed an exclusive project development agreement with our material supply partner, who has decades of experience in managing co-products from steel production, is a world leader in understanding the chemistry and mineralogy of slags and has demonstrated logistical capacity to deploy large volumes of crushed aggregate products across the U.S. and in international markets. This partnership enables us to start small in order to establish a verifiable and replicable process for optimized carbon removal, then implement this process at scale in a short amount of time.

---

[1]Lackner, K.S, et al., 1995. Carbon dioxide disposal in carbonate minerals. *Energy* 20: 1153-1170.

[2]Hartmann, J.A., et al., 2013. Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Reviews of Geophysics*. doi: 10.1002/rog.20004.

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.

Project Objectives:

(1) Expand the reach of our alkaline aggregate for gravel roads into new markets where

economic factors limit its competition with other sources of natural aggregate

(2) Optimize carbon removal with every new gravel road built using our products by altering the grain size and composition of alkaline aggregate blends

The role of carbon financing and the rates of carbon removal will dictate how far we can stretch the deployment radius of each production facility (Fig. 3). For instance, at a removal efficiency of 9.5% and a carbon removal price of \$322.45/tCO_2, we can expand our maximum deployment radius from 30 miles to 60 miles (assuming that we apply a \$0.175 per ton-mile subsidy to the current transport cost of \$0.35 per ton-mile). This doubles the plausible deployment radius around each production facility and increases the addressable deployment area by 4X (Fig. 3).

As our ability to optimize and improve carbon removal in our roads increases with iterative testing, we will be able to maintain expanded deployment radii as the price per ton decreases towards \$100/tCO_2. To improve and optimize the CDR efficiency of our aggregates, we will be exploring alterations to grain size, changes to the aggregate blend to include more reactive minerals, and modifications to deployment strategies (thinner layers, reactive top coats, etc).

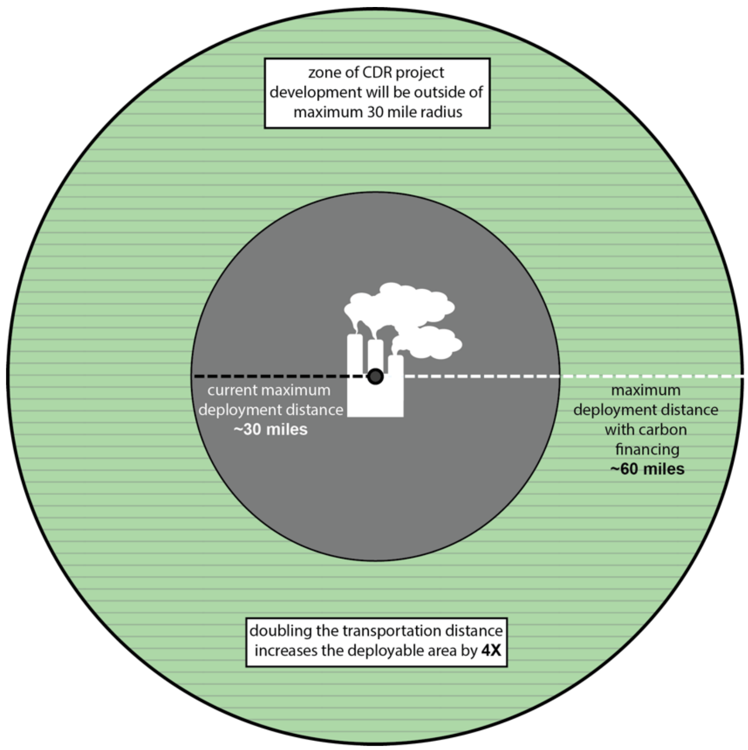

Fig. 3. Schematic showing the increase deployment area (4X) made viable with a transportation subsidy from CDR credit sales that increases maximum transport distance from 30 to 60 miles. All projects described here will take place in the green zone, beyond the current maximum deployment distance.

Location and Scale: Our pilot projects will be in Northern Indiana within reasonable proximity to a facility that produces the aggregate on site at a steel mill. We will deploy 4,000 tons of aggregate beginning this summer (2023) for our initial pilots and will do a larger deployment of 18,000 tons of aggregate during 2024 that will contribute CDR to this project. During 2023 and early 2024, we will be conducting small experimental tests on grain size and aggregate blend that will inform our 2024 deployments, which will be better optimized for CDR.

How we will reach \$100/tCO_2: There are several factors that will enable us to be cost effective at a CDR price of \$100/tCO_2. As we optimize our aggregate blends to absorb more CO_2 and increase our measurement period for CDR (1 year in this project, but materials react for at least a decade), our unit costs will improve for each ton of aggregate we deploy. In addition, as we scale our deployments the CAPEX and fixed labor costs will decrease as they are spread over more tonnage. Lastly, we expect our MRV approach to become more streamlined which will reduce costs associated with measurement in comparison to our initial projects described here.

How we reach 0.5 $GtCO_2$ of CDR: Achieving scale is an enormous challenge and one that will require creativity and flexibility by our entire industry. We plan to begin scaling by utilizing both slags produced at existing facilities each year and to also begin utilizing legacy materials on site at these same facilities. When a steel mill is first built, the local market for aggregate typically takes time to develop so the slag will be piled in large berms on site. For example, at the facility in northern Indiana where we will begin operations, there is a large berm of ~250-500K tons of unreacted slag that has a composition similar to our road aggregate that we will begin processing for projects over the next few years.

Our initial pilot projects will operate out of one production facility for simplicity. However, our material supply partner operates production facilities in 12 states in the U.S. and internationally in 12 countries across the globe (South America, Europe, Asia, Oceania) managing millions of tons of slags annually across dozens of facilities. Over time, we intend to grown into each of these markets developing high quality CDR in gravel roads across the world.

Global production of steel and iron slags is currently ~0.53-0.69 gigatons per year for both iron and steel slag[1]. Assuming a complete carbonation of these materials, using a maximum capacity of 0.4 tCO_2 per ton of slag[2], this could lead to 0.21-0.28 gigatons of CDR at current production rates. By 2100, global slag production could approach ~3 gigatons with a potential of ~1.2 gigatons of CDR[2]. Evaluating and improving upon different use cases of slag for CDR, such as gravel road surfaces, is essential to make good use of these materials for CDR.

---

[1]United States Geologic Survey, January 2022. Mineral Commodities Summary: Iron and Steel Slag. Available at: https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-iron-steel-slag.pdf

[2]Renforth, P., 2019. The negative emission potential of alkaline materials. *Nature Communications*. doi: 10.1038/s41467-019-09475-5

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 risks associated with this project include:

- **Technical:** Optimizing carbon removal in aggregate products could be difficult for a few reasons. First, the most reactive slag product is from a ladle metallurgy furnace (LMF). While reactive, this material can be difficult to manage and incorporate into aggregate products. Higher concentrations of LMF in aggregate will increase expansion, which can lead to poor performance for road surfaces depending on deployment scenarios. We intend to increase the concentration LMF beyond what is currently incorporated into the blend, but we may be limited in how high we can push this due to negative impacts on expansion. We are also exploring creating LMF topcoats, incorporating finer grained slags with substantial silicate glasses (EAF slags), or surface manipulations following deployments (increased resurfacing and grading, for instance).

- **MRV:** The risk for MRV in this application is minimal. It could be complex to differentiate carbon from mineralization reactions in our roads with underlying carbonate aggregates that pre-date the application of the product where grading is inconsistent or upper layer of road has been mixed with underlying layers. We will avoid these scenarios in our initial deployments (easier to do on driveways and parking lot applications), and have plans to explore this with carbon isotopes (^{14}C and stable isotope approaches) for future work.
- **Ecosystem:** With any gravel road application, there is some risk for contamination with dust or loose material entering the ecosystem. If managed poorly, gravel road dust can lead to negative health outcomes[1]. However, our supply partner is an industry leader in monitoring and minimizing risk through high quality standards, and proper deployment/management for all road surfaces. All of our products are consistently measured and evaluated for metals, both in absolute concentrations and in leaching tests, and there have been no reported issues with dust contamination. Additionally, our products self-cement through reaction with CO_2, which helps stabilize the road surface and minimize dust and runoff impacts over time.

---

[1]Khan and Strand, 2019. Road dust and its effect on human health: a literature review. *Epidemiol Health*. doi: 10.4178/epih.e2018013

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)*	1,551 tCO_2
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	December 2025
Levelized Price (\$/ton CO_2)* *(This is the price per ton of your offer to us for the tonnage described above)*	\$322.45/tCO_2

** 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]