

General Application

(The General Application applies to everyone, all applicants should complete this)

Company or organization name

Equiopps (aka "Heirloom Carbon Technologies")

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

San Francisco, CA

Name of person filling out this application

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Email address of person filling out this application

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Brief company or organization description

Low Cost Direct Air Capture via Mineralization

1. Overall CDR solution (All criteria)

- a. Provide a technical explanation of the proposed project, including as much specificity regarding location(s), scale, timeline, and participants as possible. Feel free to include figures.

Magnesium and calcium-based minerals are earth-abundant and naturally uptake carbon dioxide (CO₂) as a part of the carbon cycle. Our technology works to accelerate and amplify the ways these minerals take up CO₂ in a cyclical process to repeatedly capture CO₂ directly from the atmosphere.

We aim to pursue a carbon dioxide removal approach that is cost-efficient, verifiable,

highly-durable, additional, and has limited second order impacts. This solution excels in limiting any negative environmental, social, and political impacts of carbon dioxide removal at scale, and simultaneously minimizes disruption to our fragile ecosystems.

We start with a magnesium (MgCO_3) or calcium carbonate (CaCO_3). Under high temperature conditions ($\geq 350^\circ\text{C}$ for magnesium carbonate and $\geq 825^\circ\text{C}$ for calcium carbonate), the carbonates break down into CO_2 and reactive oxides (calcium oxide (CaO) and magnesium oxide (MgO)). This process, called calcination, is commercially deployed across multiple industries, including cement and lime production. At optimal conditions, electric calcination can produce amorphous oxides that are highly reactive with CO_2 , even at atmospheric concentrations (roughly 400 parts per million CO_2 by volume). Post-calcination, the material can be placed outdoors in contact with air and naturally reform carbonate materials.

Once the oxides have sufficiently carbonated, they are collected and can be re-calcined. The carbon dioxide from the calcination is captured and stored either in geological reservoirs or by mineralization. The produced oxides can then be carbonated again, and the process can continue cyclically (Figure 1).

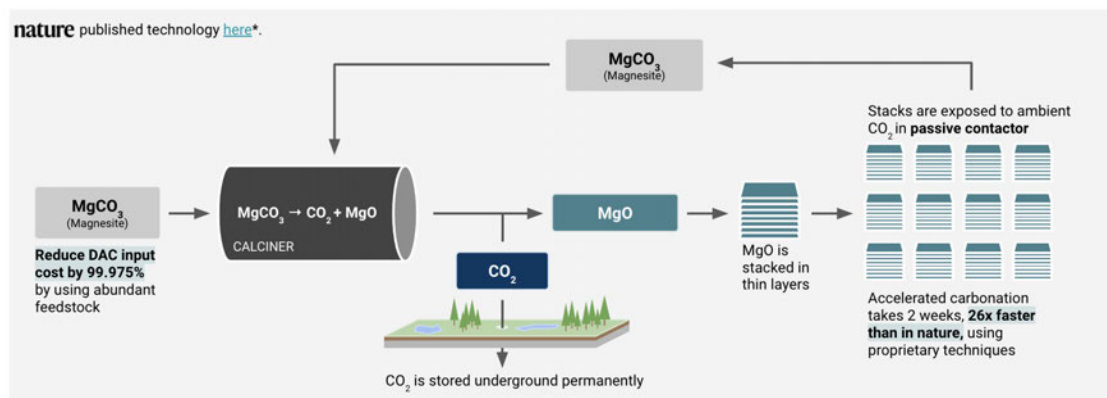


Figure 1: Oxides (represented above by magnesium oxide, MgO) are used to repeatedly capture CO_2 from the ambient air using a cyclic process that consists of capturing CO_2 (carbonation) and releasing CO_2 (calcination). The process theory is detailed in the publication [Ambient Weathering of Magnesium Oxide for CO₂ Removal from Air published in 2020 by Nature Communications](#).

We have developed a preliminary technoeconomic analysis of the process that indicates the most sensitive parameters within the process. In particular, the cost and efficacy of the passive air contactor exemplifies one area of innovation that, if developed to meet or beat the cost/performance requirements, unlocks the vast potential of carbon removal at scale. Similarly, optimizing calcination conditions to reduce feedstock deterioration and maximize reuse has a significant impact on both our overall cost and environmental impact.

To unlock the potential of this concept, we require novel and innovative research and development of the passive air contactor, or the passive CO_2 uptake mechanism, as well as continued optimization of our calcination process. In the passive air contactor, we allow air to ambiently move through the system, without being forced by fans as in similar direct air capture systems. With this passive design, we are able to cut down the capital and operational costs associated with the contactor unit, in exchange for a slightly longer time allotment for the CO_2 uptake reaction. This will allow us to achieve lower capital and operating costs than

more highly engineered systems.

If left to its own devices, the ambient carbonation process requires approximately one year, which is too slow to be economically feasible. Our lab and prototype experiments show that various proprietary techniques and optimized calcination conditions consistently increase the rate of reaction by over an order of magnitude for both MgO and CaO feedstocks. Importantly, we can repeatedly and consistently increase the carbonation rate. Currently, the peak carbonation rates for this process indicate a 2 week carbonation time, with averages around 4 weeks. This puts us within 2x of our target carbonation time of 12.5 days average, which we believe is achievable.

To scale the process and achieve further rate advantages, we are designing an automated and modular passive air contactor that facilitates contact between the air and the adsorbent material. The passive air contactor has a crucial role to play in the process and will require iterating through different geometries and configurations to determine the optimal design for both air contacting and carbonation rate accelerants. This will allow for better air-solid contact than land-based plots, which can further increase the materials' CO₂ uptake rate, as well as decrease land area requirements.

We aim to deploy a fully integrated demo-scale plant in the next 12-18 months, followed by a commercial plant (100,000 tCO₂/year).

- b. What is your role in this project, and who are the other actors that make this a full carbon removal solution? *(E.g. I am a broker. I sell carbon removal that is generated from a partnership between DAC Company and Injection Company. DAC Company owns the plant and produces compressed CO₂. DAC Company pays Injection Company for storage and long-term monitoring.)*

Heirloom is a carbon capture solution. We sell carbon removal credits that are generated from a partnership between ourselves, the DAC company, and an Injection Company (TBD). We own the plant and produce compressed CO₂, and pay an Injection Company for storage and long-term monitoring. Additionally, we may end-of-life some net-negative mineralized carbonate and sell or distribute a small percentage of captured CO₂ to companies utilizing CO₂ in durable products.

- c. What are the three most important risks your project faces?

There are several risks, both technical and financial, associated with bringing the oxide looping innovation to market. Technically, the greatest risks are two-fold: (1) Migrating a lab-based concept to a commercial scale passive air contactor at low cost, and (2) demonstrating the integrated carbonation-calcination system over repeated cycles. Financially, the greatest risk is attracting sufficient market demand to satisfy lender requirements and finance our commercial operation (100,000+ ton plant).

Passive air contactor: Here, the greatest challenge will be designing the passive air contactor to facilitate contact between the air and metal oxides in a way that allows us to achieve the

observed CO₂ uptake rates from laboratory experiments on the demo scale. This has never been done before, so there is inherent risk in achieving the desired uptake rate. There are 7 key passive air contactor efficiency milestones that need to be met in order to achieve our overall cost targets of \$100/tCO₂ at 1M tons scale, and <\$50/tCO₂ longer term.

Repeated cycling: The second risk involves demonstrating the integrated system on the demonstration scale. While this is also of paramount importance to the process viability, the calcination process is used industrially to mass produce cementitious materials and, therefore, poses less of a risk than the passive air contactor design. That being said, there are still risks associated with the calcination process that need to be measured, understood, and optimized before achieving commercial scale.

Financing: The primary financial risk associated with bringing our innovation to market is the need to formalize sufficient long-term (5+ year) offtake contracts to cover debt service and operations for a commercial plant.

d. If any, please link to your patents, pending or granted, that are available publicly.

- <https://patents.google.com/patent/WO2020263910A1/en>

2. Timeline and Durability (Criteria #4 and Criteria #5)

a. Please fill out the table below.

	Timeline for Offer to Stripe
<p>Project duration</p> <p><i>Over what duration will you be actively running your DAC plant, spreading olivine, growing and sinking kelp, etc. to deliver on your offer to Stripe? E.g. Jun 2021 - Jun 2022. The end of this duration determines when Stripe will consider renewing our contract with you based on performance.</i></p>	<p><10 words</p> <p>Delivery: June 2021 - December 2023</p> <p>Renewal evaluation: December 2022</p>
<p>When does carbon removal occur?</p> <p><i>We recognize that some solutions deliver carbon removal during the project duration (e.g. DAC + injection), while others deliver carbon removal gradually after the project</i></p>	<p><10 words</p> <p>June 2021 - December 2023</p>

<p>duration (e.g. spreading olivine for long-term mineralization). Over what timeframe will carbon removal occur?</p> <p><i>E.g. Jun 2021 - Jun 2022 OR 500 years.</i></p>	
<p>Distribution of that carbon removal over time</p> <p><i>For the time frame described above, please detail how you anticipate your carbon removal capacity will be distributed. E.g. “50% in year one, 25% each year thereafter” or “Evenly distributed over the whole time frame”. We’re asking here specifically about the physical carbon removal process here, NOT the “Project duration”. Indicate any uncertainties, eg “We anticipate a steady decline in annualized carbon removal from year one into the out-years, but this depends on unknowns re our mineralization kinetics”.</i></p>	<p>~5% in year 1, ~25% in year 2, ~70% in year 3.</p> <p>We anticipate a non-linear ramp of carbon removal capacity from <1tCO₂/year today to 1tCO₂/day at our demo plant, scheduled to be live in Q3 2022. We expect our capacity to be capped at ~1tCO₂/day in our demo plant.</p>
<p>Durability</p> <p><i>Over what duration you can assure durable carbon storage for this offer (e.g. these rocks, this kelp, this injection site)? E.g. 1000 years.</i></p>	<p>Short term: there is uncertainty around the durability of our removal, but will consist of a combination of geological storage and commercial utilization in durable goods.</p> <p>Long term: Geological storage and ex-situ mineralization, 1,000+ years</p>

b. What are the upper and lower bounds on your durability claimed above in table 2(a)?

<p>Geologic Storage: > 1,000 years</p> <p>Utilization: 1 - 1,000 years, where 1 year represents lower durability processes, such as chemical production, and 1,000+ years includes utilization-based storage opportunities, such as CO₂ curing.</p>

c. Have you measured this durability directly, if so, how? Otherwise, if you’re relying on the literature, please cite data that justifies your claim. (E.g. We rely on findings from Paper_1 and Paper_2 to estimate permanence of mineralization, and here are the reasons why these findings apply to our system. OR We have evidence from this pilot project we ran that biomass sinks to D ocean depth. If biomass reaches these depths, here’s what we assume happens based on Paper_1 and Paper_2.)

We have not directly measured the durability of our carbon storage. Heirloom's process relies on a storage partnership downstream of the pure CO₂ production. Mechanisms for geologic storage are well-developed and available in the scientific literature and include structural, capillary, solubility and mineral trapping of the CO₂ in suitable geologic reservoirs. These estimates are used to formulate the range presented above. You can find the referenced ranges in [Chapter Seven of the NASEM report on Negative emissions](#) and reliable sequestration, as well as corroborated in [Kelemen et al.\(2019\)](#) and [de Coninck and Benson \(2014\)](#). An important siting aspect for this technology will be co-location with either (a) a CO₂ sequestration location or (b) CO₂ transportation infrastructure, including pipelines or railways. Additionally, the likelihood of leakage during geologic storage are modeled in [Alcolde et al. \(2018\)](#).

This storage could also be in the form of mineralization via partnerships with a company like CarbFix. These mineralization processes inject dissolved CO₂ into suitable basins - basaltic basins in the case of CarbFix - where the dissolved CO₂ mineralizes to become calcium carbonates. This process is outlined in the [Matter et al. \(2019\)](#).

- d. What durability risks does your project face? Are there physical risks (e.g. leakage, decomposition and decay, damage, etc.)? Are there socioeconomic risks (e.g. mismanagement of storage, decision to consume or combust derived products, etc.)? What fundamental uncertainties exist about the underlying technological or biological process?

The primary risks associated with durability are physical (i.e. leakage from the geologic storage basin). The likelihood of leakage during geologic storage are modeled in [Alcolde et al. \(2018\)](#). Factors for CO₂ leakage, as well as basin geology and CO₂ trapping mechanisms, must be taken into consideration when siting geologic storage projects to mitigate the chance of re-releasing CO₂ into the atmosphere.

In the case that the storage mechanism involves mineralization, such as is the case with CarbFix, the risk of re-release is greatly reduced as the carbon is mineralized on the order of years.

- e. How will you quantify the actual permanence/durability of the carbon sequestered by your project? If direct measurement is difficult or impossible, how will you rely on models or assumptions, and how will you validate those assumptions? *(E.g. monitoring of injection sites, tracking biomass state and location, estimating decay rates, etc.)*

The permanence/durability of the carbon stored will be quantified by measuring the CO₂ injection into the geologic storage reservoir. This includes post-injection monitoring and verification by the storage entity, as defined by any formal contract between Heirloom and the chosen CO₂ storage entity. Monitoring includes tracking the physical plume of CO₂ in the subsurface via seismic imaging, pressure data from injection wells to monitor for pressure buildup and ensure caprock integrity, and employing methods to detect CO₂ leakage, such as eddy-covariance towers or CO₂ flux chambers. An example of monitoring and verification protocol for the Cranfield Project is available in [Hovorka et al \(2013\)](#). Other projects monitoring

protocols are also available in the literature, primarily for pilot projects.

3. Gross Capacity (Criteria #2)

- a. Please fill out the table below. **All tonnage should be described in metric tonnes here and throughout the application.**

	Offer to Stripe (metric tonnes CO ₂) over the timeline detailed in the table in 2(a)
Gross carbon removal Do not subtract for embodied/lifecycle emissions or permanence, we will ask you to subtract this later	50 tCO ₂
If applicable, additional avoided emissions e.g. for carbon mineralization in concrete production, removal would be the CO ₂ utilized in concrete production and avoided emissions would be the emissions reductions associated with traditional concrete production	N/A

- b. Show your work for 2(a). How did you calculate these numbers? If you have significant uncertainties in your capacity, what drives those? (E.g. *This specific species sequesters X tCO₂/t biomass. Each deployment of our solution grows on average Y t biomass. We assume Z% of the biomass is sequestered permanently. We are offering two deployments to Stripe. $X \cdot Y \cdot Z \cdot 2 = 350 \text{ tCO}_2 = \text{Gross removal}$. OR Each tower of our mineralization reactor captures between X and Y tons CO₂/yr, all of which we have the capacity to inject. However, the range between X and Y is large, because we have significant uncertainty in how our reactors will perform under various environmental conditions*)

Our total capacity is a function of the total capture per rack per cycle, time per cycle, number of racks deployed, and calcination throughput. We have calculated the value above based on a conservative estimate of our planned ramp from today's prototype capacity to our projected demo plant capacity, scheduled for completion in 2022.

While we have established baseline carbonation rates in a lab setting (<1kg/cycle), we are in

the process of reliably reproducing these results at a prototype scale. Our current prototype rack has the capacity to capture <1 tCO₂/rack/year. According to the milestones outlined below, we have a detailed roadmap to iteratively expand both the capacity per rack and the total number of deployed racks. Our maximum demo capacity is dictated by the total volume required to validate the cost and feasibility of our integrated commercial design. Our plan of record yields a total demo capacity of ~ 350 tCO₂/year by the end of 2022.

There is significant uncertainty around our total deployed capacity by the end of 2023, with a likely range between 175-750 tCO₂/year. This uncertainty arises from (1) effects on the performance of our system in uncontrolled environments and (2) the minimum system throughput needed to gain confidence in our commercial OpEx and CapEx for both the individual subcomponents and the integrated system as a whole. As a result, we are offering Stripe a conservative 50 tCO₂ removed to ensure we can easily satisfy our commitment.

- c. What is your total overall capacity to sequester carbon at this time, e.g. gross tonnes / year / (deployment / plant / acre / etc.)? Here we are talking about your project / technology as a whole, so this number may be larger than the specific capacity offered to Stripe and described above in 3(b). We ask this to understand where your technology currently stands, and to give context for the values you provided in 3(b).

Our total capacity to sequester carbon at this time is <1 tCO₂/year. Our projected total capacity is 175-750 tCO₂/year by the end of 2022.

- d. We are curious about the foundational assumptions or models you use to make projections about your solution's capacity. Please explain how you make these estimates, and whether you have ground-truthed your methods with direct measurement of a real system (e.g. a proof of concept experiment, pilot project, prior deployment, etc.). We welcome citations, numbers, and links to real data! (E.g. *We assume our sorbent has X absorption rate and Y desorption rate. This aligns with [Sorbent_Paper_Citation]. Our pilot plant performance over [Time_Range] confirmed this assumption achieving Z tCO₂ capture with T tons of sorbent.*)

There are a number of foundational assumptions that drive our projections. First, we estimate that global feedstock availability will not be a rate limiter for our system. There are billions of tons of known and surveyed calcium carbonate and magnesium carbonate in the Earth's crust (see [USGS Mineral Commodity Summary](#) p. 97 for limestone production [aka, calcium carbonate] and p. 101 for magnesium carbonate [or [Statista](#)]). The USGS commodity summary lists reserves for calcium carbonate as 'adequate for the countries listed' as they are very large.

Second, we make assumptions around our capacity based on academic literature and our own lab and prototype experiments conducted over the last 2 years. In our experiments, we have used industrially produced calcium oxides and hydroxides to uptake CO₂ to a suitable carbonation extent within 1 month of exposing the material to air, and achieved peak carbonation rates of 2 weeks. We estimate that we can maintain this uptake rate with minimal deterioration in the uptake capacity for at least 10 cycles and as much as 100 cycles ([see Ho](#)

[et al \(2017\)](#), [Guo et al. \(2019\)](#), and [Erans et al. \(2020\)](#)). While both the academic literature and industrial production of oxides corroborate these assumptions, we are also optimizing our own calcination conditions to achieve these cycle counts in practice. As a representative example, if we were to use 1 years worth of global CaCO_3 production in our looping process under optimal material loss conditions, and assume 10 cycles of reuse, we could capture 1.4 billion tons of CO_2 /year.

- e. Documentation: If you have them, please provide links to any other information that may help us understand your project in detail. This could include a project website, third-party documentation, project specific research, data sets, etc.

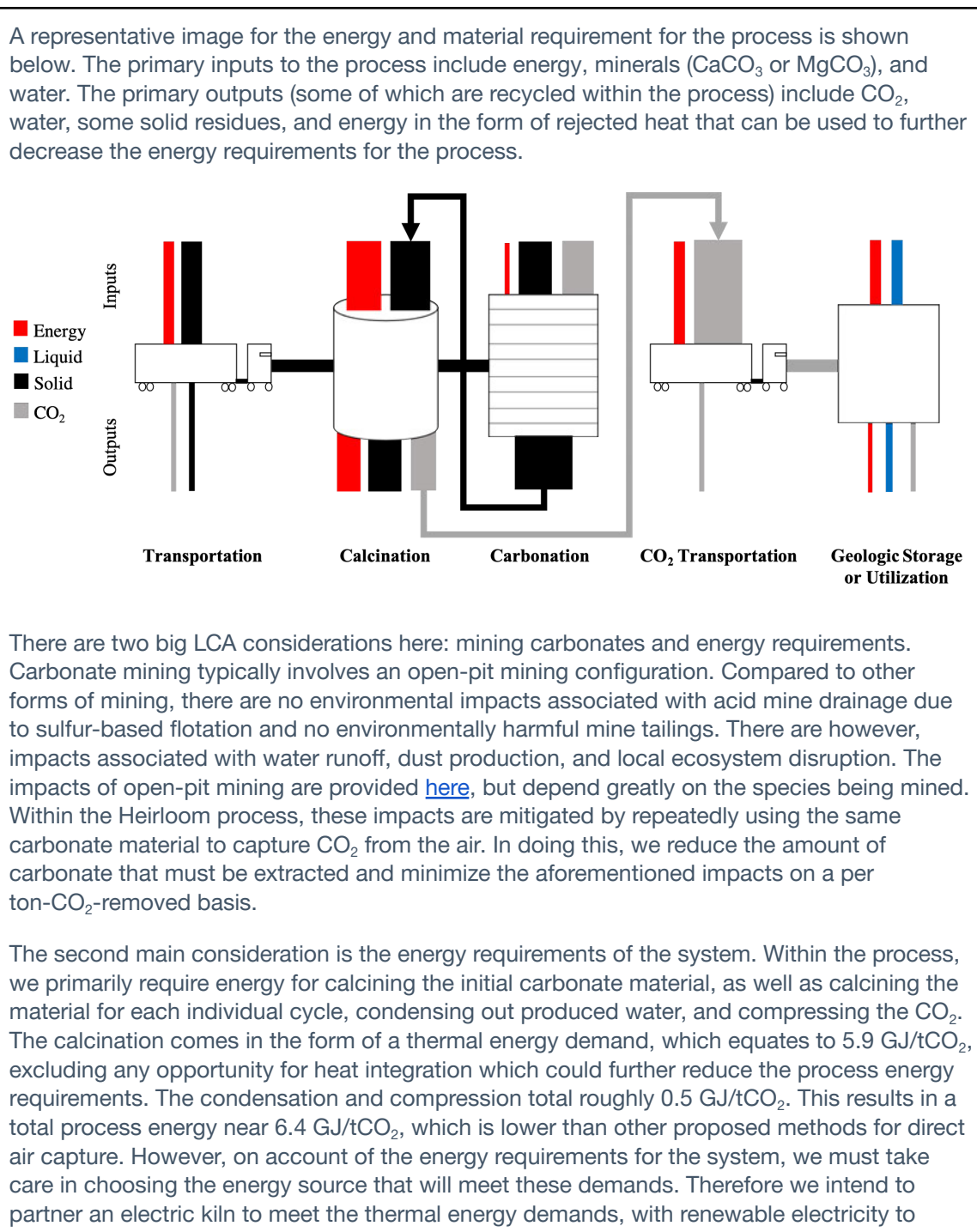
- A link to the concept paper for the oxide looping process (using magnesium oxide) is provided [here](#).
- The process is also discussed in [Kelemen et al. \(2020\)](#).

4. Net Capacity / Life Cycle Analysis (Criteria #6 and Criteria #8)

- a. Please fill out the table below to help us understand your system's efficiency, and how much your lifecycle deducts from your gross carbon removal capacity.

	Offer to Stripe (metric tonnes CO_2)
Gross carbon removal	50 t CO_2
Gross project emissions	3 t CO_2e Note: while we have not yet completed a comprehensive, third-party LCA, we have completed the process flow and carbon balance below, and applied a generous buffer to estimate our emissions/removal ratio here. We estimate that the actual Scope 3 impact will be negligible due to the repeated cycling of feedstock and amortization of plant embodied emissions over a 20 year lifetime.
Emissions / removal ratio	.06
Net carbon removal	47 t CO_2e

- b. Provide a carbon balance or “process flow” diagram for your carbon removal solution, visualizing the numbers above in table 4(a). Please include all carbon flows and sources of energy, feedstocks, and emissions, with numbers wherever possible (E.g. see the generic diagram below from the *CDR Primer*, *Charm’s application* from last year for a simple example, or *CarbonCure’s* for a more complex example). If you’ve had a third-party LCA performed, please link to it.



provide these energy requirements. Many direct kiln configurations are suitable for this approach.

While a complete LCA, including multiple environmental impact categories has yet to be completed, a carbon balance is provided for the overall system in the following tables. The life cycle assessment assumes the following carbon intensities for the proposed process stages.

Greenhouse Gas Accounting Inventory

Category	Carbon Intensity
Carbonate mining Emissions [Source]	10 kg per ton mineral
Electricity (Wind Energy) [Source]	0.010 kgCO ₂ e/kWh
Electricity (Natural Gas Electricity) [Source]	0.402 kgCO ₂ e/kWh
Electricity (Solar Energy) [Source]	0.025 kgCO ₂ e/kWh
Electricity (Grid Electricity) [Source]	0.540 kgCO ₂ e/kWh

The above inventory is used in conjunction with a preliminary process flow to determine the equivalent carbon emissions from the process.

Greenhouse Gas Scope 1 and Scope 2 Emissions at a scale of 1 million tons of CO₂ per year

Category	Emissions [tCO ₂ e/tCO ₂ removed]
Carbonate Mining Emission (Assuming 1% loss per cycle)	3E-4
Electricity (Wind Energy)	0.02
Electricity (Natural Gas Electricity)	0.88
Total Emissions Wind [tCO₂e/tCO₂ removed]	0.02
Total Emissions Natural Gas [tCO₂e/tCO₂ removed]	0.9

These results show similar results to the preliminary carbon accounting included in the published techno-economic analysis of the process ([here](#)). In the published paper, the looping process uses an oxy-fired calciner, which requires a pure oxygen and natural gas feed to completely co-capture the water and CO₂ produced from the combustion process. This minimizes the electricity requirements of the system, but builds a reliance on fossil energy that is not advantageous to the process. For thorough evaluation, we have also provided the results from this initial analysis below.

Greenhouse Gas Emissions: Preliminary Carbon Accounting from [McQueen et al., 2020](#) solar and grid electricity scenarios

Category	Emissions [tCO ₂ e/tCO ₂ removed]
Carbonate Mining Emissions (Assuming a conservative 10% loss per cycle)	0.0029
Electricity (Solar)	0.0021
Electricity (Grid Electricity)	0.046
Total Emissions Solar [tCO₂e/tCO₂ removed]	0.005
Total Emissions Grid [tCO₂e/tCO₂ removed]	0.05

*Emissions from natural gas combustion are co-captured by the calcination step.

- c. Please articulate and justify the boundary conditions you assumed above: why do your calculations and diagram include or exclude different components of your system?

This includes emissions directly from the process (Scope 1 Emissions), as well as those associated with mining the carbonate mineral, energy production, and subsequent sequestration (Scope 2 Emissions). The carbon accounting does not include embodied emissions associated with constructing the process (Scope 3 emissions) or CO₂ leakage from storage reservoirs, if any. Note that there is a substantial buffer provided in Gross Project Emissions and Emissions/Removal Ratio above to account for this.

- d. Please justify all numbers used in your diagram above. Are they solely modeled or have you measured them directly? Have they been independently measured? Your answers can include references to peer-reviewed publications, e.g. [Climeworks LCA paper](#).

The values presented in the diagram are solely modeled from existing literature on the CO₂ intensity of various aspects of the looping process. Each emissions factor source is provided in the above tables from the literature or other sources. The emissions from each facet of the process is determined based on material flows and energy requirements for the oxide looping process.

The references preliminary carbon accounting and process diagram is presented in the [MgO looping preliminary techno-economic analysis paper](#).

- e. If you can't provide sufficient detail above in 4(d), please point us to a third-party independent verification, or tell us what an independent verifier would measure about

your process to validate the numbers you've provided. (We may request such an audit be performed.)

N/A

5. Learning Curve and Costs (Backward-looking) (Criteria #2 and #3)

We are interested in understanding the [learning curve](#) of different carbon removal technologies (i.e. the relationship between accumulated experience producing or deploying a technology, and technology costs). To this end, we are curious to know how much additional deployment Stripe's procurement of your solution would result in. (There are no right or wrong answers here. If your project is selected we may ask for more information related to this topic so we can better evaluate your progress.)

- a. Please define and explain your unit of deployment. (E.g. # of plants, # of modules) (50 words)

Our system consists of two main subcomponents - passive air contactors and calciners - whose combined throughput defines our unit of deployment. These two represent the bulk of our capital expenditure, while sorbent minerals are a small portion of the cost. Calciners, and electric ones in particular, have potentially steep learning curves. They are custom built today and require huge amounts of labor. Also, their material costs decrease quickly as a function of throughput because a cylindrical volume increases by a cube function while materials cost increases by a square function. As we standardize and scale up, we expect per unit cost to drop 10-15% for every doubling of capacity for calciner. Similarly, our passive air contactor will lack automation and require significant labor at the beginning, but will get cheaper as we standardize, automate, and mass produce them.

- b. How many units have you deployed from the origin of your project up until today? Please fill out the table below, adding rows as needed. Ranges are acceptable if necessary.

Year	Units deployed (#)	Unit cost (\$/unit)	Unit gross capacity (tCO ₂ /unit)	Notes
2021	Racks: 1 Calciners: <1 t/day	\$20,000	.7tCO ₂ /year	We began transitioning from lab to prototype scale in January, 2021. Our initial focus is on replicating our lab scale carbonation observations at a 1,000x scale up of our passive air contactor capacity (i.e.

				<p>racks). We are also establishing baselines for each of our key looping metrics at kg scale. Because we are iterating quickly, this cost is an estimate, not exact.</p> <p>We will continue iterating on the design, quantity, complexity, size and carbonation enhancement techniques of our tray/rack configuration. We will also optimize calcination conditions at <1 ton scale.</p>
2020	<p>Racks: <1</p> <p>Calciners: 0</p>	~\$100,000	<50kg/year	All operations in 2020 were at lab scale.

- c. Qualitatively, how and why have your deployment costs changed thus far? (E.g. *Our costs have been stable because we're still in the first cycle of deployment, our costs have increased due to an unexpected engineering challenge, our costs are falling because we're innovating next stage designs, or our costs are falling because with larger scale deployment the procurement cost of third party equipment is declining.*)

Our costs have decreased as a result of transitioning from bench to prototype scale. We are still in our first stage of prototype deployment so our costs have not changed significantly since then.

- d. How many additional units would be deployed if Stripe bought your offer? The two numbers below should multiply to equal the first row in table 3(a).

# of units	Unit gross capacity (tCO ₂ /unit)
<p>Racks: 4</p> <p>Calciner throughput: .15 t media/day</p>	13 tCO ₂ /year

6. Cost and Milestones (Forward-looking) (Criteria #2 and #3)

We ask these questions to get a better understanding of your growth trajectory and inflection points, there are no right or wrong answers. If we select you for purchase, we'll expect to work with you to understand your milestones and their verification in more depth.

- a. What is your cost per ton CO₂ today?

At lab scale we have yet to capture 1 tCO₂.

At prototype scale, our cost is ~\$20,000/tCO₂.

At 1 tCO₂/day scale, our projected cost is ~\$8,500/tCO₂.

- b. Help us understand, in broad strokes, what's included vs excluded in the cost in 6(a) above. We don't need a breakdown of each, but rather an understanding of what's "in" versus "out."

As of today we include the following in our costs:

- The cost of feedstock
- The capital expenditure of racks, including construction and materials
- The capital expenditure and vendor fees associated with buying, operating and/or outsourcing a calciner
- Energy required to operate racks and rack sensors
- Energy required to operate the calciner
- Labor

The following are not included in our costs:

- R&D
- Auxiliary operating expenditure (e.g. water use, environmental control in lab, etc.)

- c. List and describe **up to three** key upcoming milestones, with the latest no further than Q2 2023, that you'll need to achieve in order to scale up the capacity of your approach.

Milestone #	Milestone description	Why is this milestone important to your ability to scale? (200 words)	Target for achievement (eg Q4 2021)	How could we verify that you've achieved this milestone?
1	Build a functional rack prototype that replicates laboratory uptake	So far, we have reliably and reproducibly observed our key	Q2 2021	Heirloom can provide an experimental report and

	rates.	process metrics at a lab scale. This milestone allows us to show that those assumptions still hold in a controlled environment for a modular, scalable rack design. This is the milestone we are currently working towards, and will allow us to move forward with a preliminary commercial rack design and configuration for our integrated passive air contactor.		photos/videos that describe our carbonation rate and rack design in a controlled environment.
2	Reach target carbonation and degradation rates in a real world, scaled down setting.	<p>Both lab and prototype results are observed in controlled environments. While this gives us maximum carbonation and degradation rates we might achieve, it's not perfectly reflective of an operational commercial deployment.</p> <p>There are two fundamental questions we need to answer by operating in a real world setting. (1) How are carbonation and degradation rates impacted when limiting environmental controls, and how</p>	Q3/4 2021	Heirloom can provide experimental results that show our peak and average carbonation rates, feedstock degradation, and activation rate post cycling.

		<p>are they impacted by a feasible commercial rack configuration, and (2) how much feedstock will we need to replace due to material loss and degradation?</p> <p>Because both of these questions are key drivers of cost and scale, these are vital to answer as quickly as possible.</p>		
3	<p>Reach target material loss, carbonation rate, and degradation rate in a fully integrated process in a real world setting within CapEx and OpEx targets.</p>	<p>This represents the successful operation of the 1 tCO₂/day demo plant with a design that will achieve unit-profitability at 100k tCO₂/year.</p> <p>We aim to show that we can operate a scaled down version of our integrated end-to-end commercial process, and do so within our CapEx and OpEx budgets. This plant will retire all technical, financial, health, and safety risks associated with our system, and will provide the basis on which we sign long-term offtake contracts and finance our commercial plant.</p>	Q2 2022	<p>Heirloom will provide a report that describes the status of each of our 8 key air contactor and looping milestones, and a summary of the cost assumptions associated with scaling up this design to 100k tCO₂/year.</p>

i. How do these milestones impact the total gross capacity of your system, if at all?

Milestone #	Anticipated total gross capacity prior to achieving milestone (ranges are acceptable)	Anticipated total gross capacity after achieving milestone (ranges are acceptable)	If those numbers are different, why? (100 words)
1	<1tCO ₂ /year	3-5tCO ₂ /year	In milestone 1, we will scale up from lab scale results to reliable reproduction of lab results on a small number of prototype racks in a controlled environment. This will increase the number of deployed units and their efficiency, thereby increasing our total gross capacity.
2	3-5 tCO ₂ /year	10-15 tCO ₂ /year	In milestone 2, we will deploy additional racks while trying to reproduce environmentally controlled results in an uncontrolled environment. We expect to see impacts in carbonation rate and material loss that may reduce our efficiency, but aim to achieve results as close as possible to a controlled setting.
3	10-15 tCO ₂ /year	175-750 tCO ₂ /year	In milestone 3, we will build a demo plant to retire all of our technical risk. Doing so will require increasing the size of our plant over 10 fold, fully integrating our air contactor and calcination process.

d. How do these milestones impact your costs, if at all?

Milestone #	Anticipated cost/ton prior to achieving milestone (ranges are acceptable)	Anticipated cost/ton after achieving milestone (ranges are acceptable)	If those numbers are different, why? (100 words)
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1	~\$20,000	~\$15,000	The cost reduction in this milestone is largely attributable to an increase in our projected carbonation rate, and therefore an increased per-rack capacity. Increasing capacity while holding CapEx constant will reduce our costs.
2	~\$15,000	~\$15,000	We don't expect a significant reduction in cost at this stage, as we are simply validating that the observed rates from the previous milestone still hold at a slightly larger scale with limited environmental control. It is possible we will see a small increase in cost/ton at this stage.
3	~\$15,000	~\$8,500	The cost reduction in this step is a result of improved integration of our system, increased carbonation rate, and reduced cost of calcination and testing by bringing our equipment in house.

- e. If you could ask one person in the world to do one thing to most enable your project to achieve its ultimate potential, who would you ask and what would you ask them to do?

The most impactful thing anyone could do for our project would be to implement a broad, durable, multi-national carbon pricing policy that puts an accurate price on carbon emissions, and includes incentives for both decarbonization and permanent carbon dioxide removal technologies.

- f. Other than purchasing, what could Stripe do to help your project?

There are four things that Stripe could do to help our project: 1) continue to push the envelope on corporate environmental responsibility, and encourage other companies to do so as well, 2) set a high bar for the level of quality in carbon dioxide removal, 3) elevate carbon dioxide

removal businesses with PR and co-marketing opportunities, and 4) advocate for stronger carbon-dioxide-removal-related policy at the state and federal level.

7. Public Engagement and Environmental Justice (Criteria #7)

In alignment with Criteria 7, Stripe requires projects to consider and address potential social, political, and ecosystem risks associated with their deployments. Projects with effective public engagement tend to do the following:

- Identify key stakeholders in the area they'll be deploying
- Have some mechanism to engage and gather opinions from those stakeholders and take those opinions seriously, iterating the project as necessary.

The following questions are for us to help us gain an understanding of your public engagement strategy. There are no right or wrong answers, and we recognize that, for early projects, this work may not yet exist or may be quite nascent.

- a. Who are your external stakeholders, where are they, and how did you identify them?

Our key stakeholders today are primarily business stakeholders. They include customers (voluntary buyers, compliance market participants, and CO₂ utilization buyers), academic and research institutions, government grant agencies, investors, supply chain partners and vendors, recruits, employees, and policy and climate advocacy groups at the regional and national level.

In addition, we frequently engage with Carbon180 on policy and environmental issues, and with the California Air Resources Board to better understand the permitting, legal, environmental, and compliance landscape for deploying Direct Air Capture technologies.

We have not yet deployed our solution at demo scale, nor have we chosen a location for our commercial plant.

- b. If applicable, how have you engaged with these stakeholders? Has this work been performed in-house, with external consultants, or with independent advisors?

We have engaged these stakeholders through a combination of in-house engagement, external consultants, and advisors.

- c. If applicable, what have you learned from these engagements? What modifications have you already made to your project based on this feedback, if any?

The most substantial modification to our project is a result of our engagements with Carbon180, which have considerably impacted our system design. Our original design consisted of a single ex-situ mineralization plot spread over a large land area in non-arable,

desert areas. The environmental consequences of substantial land use in desert areas are clear, though (in particular on biodiversity and plant/animal species) and we have since adjusted our thinking around land use. The adjusted “rack” design reduces our land use requirements by over 100x while reducing the physical impact on fragile ecosystems.

- d. Going forward, do you have changes planned that you have not yet implemented? How do you anticipate that your processes for (a) and (b) will change as you execute on the work described in this application?

While we will continue to proactively engage with the stakeholders in (a) as early as possible in our commercial and demo deployment, there are three important focus areas for our company over the next two years. 1) we plan to reduce negative environmental externalities by increasing the number of cycles our sorbent can undergo, which has direct implications on our embodied emissions, land use, and transportation emissions. 2) We are cautious of placing plants in high power demand areas and using substantial energy from the grid. We plan to use dedicated onsite renewable energy to power most of our operations in order to avoid impacting electricity prices and supply for local communities. 3) We understand that we are dealing with powders and, as we transition to a real world, limited-control environment, will need to take extreme care in ensuring we don’t let them mix with air. A primary goal of ours this year is to quantify and minimize material loss. We will satisfy OSHA requirements to protect our employees and carefully study the environmental impact of our system at scale.

- e. What environmental justice concerns apply to your project, if any? How do you intend to consider or address them?

One of the primary environmental justice benefits of Heirloom’s technology is that commercial deployments can be sited in declining oil, gas, and coal regions to revitalize communities with better access to high paying jobs. There is significant overlap between non-arable land, injection expertise and infrastructure, and ambient conditions suitable for optimal carbonation rates. Our technology is well suited to operate in these areas.

11. Legal and Regulatory Compliance (Criteria #7)

- a. What legal opinions, if any, have you received regarding deployment of your solution?

While we haven’t received formal legal opinions on the matter, Stanford’s Carbon Storage department and California Air Resources Board (CARB) have informed us that insofar as the project follows the regulatory requirements for Class VI wells (see below), which are used for long term storage of CO₂ into geologic formations, our process is both legal and compliant.

- b. What permits or other forms of formal permission do you require, if any? Please clearly differentiate between what you have already obtained, what you are currently in the process of

obtaining, and what you know you'll need to obtain in the future but have not yet begun the process to do so.

We have not yet begun any permitting processes, but we will be satisfying all the requirements of the CCS protocol of the California Low Carbon Fuel Standard (LCFS) program, whose permanence requirements go beyond the federal requirements for both Class II and Class VI wells (the latter of which are required to qualify for 45Q tax credit). We will be partnering with a CO₂ storage vendor for our initial commercial plants to fast track these permits. Some permits and approvals we will need are:

1. Class VI permit as required under the Underground Injection Control ("UIC") Program. These requirements are created under the authority of Safe Drinking Water Act ("SDWA") to protect public health from water contamination. The site characterization, well construction, operating, testing, well plugging, and post injection requirements are all listed [here](#). To receive credits from LCFS, we have to satisfy these requirements.
2. EPA-approved site specific monitoring, reporting and verification plan, as required under Subpart RR of the GHG Reporting program.

- c. In what areas are you uncertain about the legal or regulatory frameworks you'll need to comply with? This could include anything from local governance to international treaties. For some types of projects, we recognize that clear regulatory guidance may not yet exist.

Underground Injection Program ("UIC") has, for better or worse, been around for a long time with stable requirements and there are many experts/consultants/vendors we can leverage to procure them. Having said that, there are some uncertainties:

1. Will each US state have different injection control requirements? (eg. California is more stringent than federal)
2. Will the permitting process take longer than 2 years, which we are currently budgeting?
3. How much cost will permitting and monitoring add to our process, in particular if/when requirements become more stringent?

12. Offer to Stripe

This table constitutes your offer to Stripe, and will form the basis of our expectations for contract discussions if you are selected for purchase.

	Offer to Stripe
Net carbon removal (metric tonnes CO ₂)	47 tCO ₂

Delivery window (at what point should Stripe consider your contract complete?)	June 2021-December 2023
Price (\$/metric tonne CO ₂) <i>Note on currencies: while we welcome applicants from anywhere in the world, our purchases will be executed exclusively in USD (\$). If your prices are typically denominated in another currency, please convert that to USD and let us know here.</i>	\$10,000 This is a projected blended average of our costs over the duration of the engagement, and is not substantively different than our costs.

Application Supplement: DAC

(Only fill out this supplement if it applies to you)

Note: these questions are with regards only to air capture: e.g. your air contactors, sorbents or solvents, etc. Separately, there exist Geologic Injection and CO₂ Utilization supplements. We anticipate that most companies filling out this DAC supplement should ALSO fill out one of those supplements to describe their use of the CO₂ stream that's an output of the capture system detailed here.

Physical Footprint (Criteria #1 and #2)

1. What is the physical land footprint of your project, and how do you anticipate this will change over the next few years? This should include your entire physical footprint, i.e., how much land is not available for other use because your project exists.

Year	Land Footprint (km ²)
2021	0.004 km ²
2022	0.03 km ²
2023	0.03 km ²

- What is the volumetric footprint of your contactor? (How big is your physical machine compared to how much you're capturing?) and how do you anticipate this will change over the next few years? These numbers should be smaller than (1) above.

Year	Contactor Footprint (m ³)
2021	5 m ³
2022	70 m ³
2023	70 m ³

2. Capture Materials and Processes (Criteria #5, #7, and #8)

- What sorbent or solvent are you using?

Magnesium oxide and calcium oxide are both suitable sorbents.

- What is its absorption capacity? (*grams CO₂ per grams material/cycle*)

The anticipated uptake capacity for CaO is ~0.59 gCO₂ per gCaO per cycle and for MgO is ~0.82 gCO₂ per gMgO per cycle.

- What is its desorption capacity? (*grams CO₂ per grams material/cycle*)

The desorption capacity at 90% calcination efficiency is 0.53 gCO₂ per gCaO per cycle and 0.74 gCO₂ per gMgO per cycle.

- How do you source your sorbent or solvent? Discuss how this sourcing strategy might change as your solutions scales. Note any externalities associated with the sourcing or manufacture of it

(hazardous wastes, mining, etc. You should have already included the associated carbon intensities in your LCA in Section 6)

The sorbent is an Earth-abundant mineral and, as such, is mined from the Earth. As of now, we will procure carbonates from industrial suppliers. As we scale, we may integrate our supply chain to have more control over both the negative externalities and CO₂ emissions of the mining process, as well as the cost of the feedstock. Co-locating our facilities with available reservoirs for mineral feedstock and geologic storage will also cut down the number of CO₂ emissions from mineral and CO₂ transport.

The main negative externality associated with sourcing our material is increased mining operations to account for new magnesium or calcium carbonate demand.

5. How do you cycle your sorbent/solvent?

The oxide sorbent is laid out in racks where, throughout the duration of the cycle it reforms carbonates. At the end of each cycle, the carbonated material is collected and sent to a central calcination facility, where it is treated at an elevated temperature and the CO₂ is evolved from the carbonate mineral. This reproduces the oxide material for use in additional cycles while producing a near-pure stream of CO₂.

6. What is your proposed source of energy? What is its assumed carbon intensity? How will this change over the duration of your project? (You should have already included the associated carbon intensities in your LCA in Section 6)

Our proposed source of energy varies by location, but is likely either geothermal or onsite solar or wind electricity. In a first of a kind process, it is likely that we will have some grid-mix electricity. However, as we scale, we will develop renewable electricity infrastructure on the utility scale to both lower energy costs and as to not draw on grid renewable energy capacity. We expect the carbon intensity of our energy source to decrease over the duration of our project.

7. Besides energy, what other resources do you require in cycling (if any), e.g water? Where and how are you sourcing these resources, and what happens to them after they pass through your system? (You should have already included the associated carbon intensities in your LCA in Section 6) (100 words)

We require the initial carbonate minerals for use as sorbent in the process, as well as some proprietary techniques to enhance carbonation rates. The carbonates are sourced from mining operations, specifically in the form of open-pit mining, the impacts of which were previously discussed.

8. Per (7), how much of these resources do you need per cycle?

Depending on a number of unknowns, including the final configuration of our plant, calcination optimizations and operating conditions described in the milestone section, we will require some amount of water.

9. How often do you cycle your sorbent/solvent?

1 cycle every 2-4 weeks.

10. Does your sorbent or solvent degrade over time? Is degradation driven primarily by cycling, environmental conditions, or both?

While repeated cycling in an integrated system has yet to be completed, it is likely that the sorbent will degrade over time as a function of repeated cycling. This will likely occur in the form of deactivation (sintering) from the high temperature calcination step. It is possible that the deactivation can be minimized via pathways for reactivation.

11. In practical operation, how often do you need to replace your sorbent or solvent material, if at all?

Pessimistically, every 10 cycles. However, a makeup stream will be introduced to account for any losses during the cycling process. In optimistic scenarios, the sorbent could be cycled for the upwards of 100s of cycles.

12. Per (11), what happens to your sorbent/solvent at end-of-life? Please note if it is hazardous or requires some special disposal, and how you ensure end-of-life safety.

At the end of the sorbent's life, it is likely that we can do one or two things. First, we could allow the material to carbonate completely over a longer time frame, or using a higher partial pressure of CO₂. This would produce carbonates that can be used to backfill mines, or otherwise sold as aggregate or into other materials markets. Alternatively, the sintered oxide material may be of use in other materials markets, such as refractory brick for kilns. We aim to be able to upcycle the material once we have finished using it for carbon removal.

13. Several direct air technologies are currently being deployed around the world (e.g. [Climeworks](#), which Stripe purchased from in 2020). Please discuss the merits and advantages of your system in comparison to existing systems.

Our technology combines the best of DAC and carbon mineralization to create a cheap, scalable, verifiable, permanent, low land use, and less extractive capture method. Instead of custom adsorbents that can cost >\$200/kg, we instead use abundant natural minerals that are commonly used in industry and cost \$0.05/kg. Similar to how Tesla leveraged off-the-shelf lithium ion batteries for EV batteries, we can benefit from existing cheap materials to achieve low costs quickly.

The primary innovation is enhancing the carbon uptake rates of low cost alkaline minerals in an economically viable passive air contactor. The contactor allows air to flow ambiently through the material without requiring additional energy input into the system via fans or other infrastructure. With this passive design, we are able to cut down the capital costs associated with the contactor unit, in exchange for a slightly longer time allotment for the CO₂ uptake reaction. We believe passive carbonation will be significantly cheaper than existing DAC systems.

Application Supplement: Surface Mineralization

(Only fill out this supplement if it applies to you)

Source Material and Physical Footprint (Criteria #1 and #8)

1. What source material are you using, and how do you procure it?

We require the initial carbonate minerals for use as sorbent in the process. The carbonates are sourced from mining operations, specifically in the form of open-pit mining, the impacts of which were previously discussed. Today, we can procure source materials directly from suppliers, but in the future it may be advantageous to own and operate our own carbonate mines.

2. Describe the ecological impacts of obtaining your source material. Is there an existing industry that co-produces the minerals required?

The ecological impacts associated with obtaining our source material include ecosystem destruction (and erosion), dust exposure, and wastewater production. Open pit mines occur on the surface of the Earth, which means that they displace local animal habitats, which can be worsened by erosion of land. Dust, as well as CO₂ emissions, occur from mining-related activities, including blasting and grinding. Finally, water demand for mining operations can be high. Wastewater production, if improperly managed, can also pollute local freshwater streams.

It is possible that the oxide material can also be produced by cycling mafic and ultramafic mine tailings, followed by a separation of the oxides from the silica and other contaminants in the tailings.

3. Do you process that source mineral in any way (e.g grinding to increase surface area)? What inputs does this processing require (e.g. water, energy)? You should have already included their associated carbon intensities in your LCA in Section 6.)

The source material is heated in a calcination step prior to being suitable for carbon capture. This releases bound CO₂ that is then captured and stored geologically. The emissions associated with this heating are included in the process diagram and LCA discussed previously. Post-mining, the material is of suitable particle size for the process as it can decrease in particle size depending on the conditions in the calcination step.

4. Please fill out the table below regarding your project's physical footprint. If you don't know (e.g. you procure your source material from a mining company who doesn't communicate their physical footprint), indicate that in the square.

	Land area (km ²) in 2021	Competing/existing project area use (if applicable)
Source material mining	Our suppliers do not publicly communicate the details of their physical footprint, but based on available estimates of the total operational footprint (material mining and processing combined) the total land area to support our project is <.001 km ² .	Existing limestone and magnesium carbonate mines
Source material processing	This is included in the land area above.	Mine processing facility
Deployment	N/A. See deployment estimates in DAC supplement above.	

5. Imagine, hypothetically, that you've scaled up and are sequestering 100Mt of CO₂/yr. Please project your footprint at that scale (we recognize this has significant uncertainty, feel free to provide ranges and a brief description).

	Projected # of km ² enabling 100Mt/yr	Projected competing project area use (if applicable)
Source material mining	~13-50 km ² , inclusive of material processing, depending on the feedstock and mine used.	Existing limestone and magnesium carbonate mines
Source material processing	This is included in the land area above.	Mine processing facility
Deployment	N/A. See deployment estimates in DAC supplement above.	

6. If you weren't proceeding with this project, what's the alternative use(s) of your source material? What factors would determine this outcome? (E.g. *Alternative uses for olivine include X & Y. It's not clear how X & Y would compete for the olivine we use. OR Olivine would not have been mined but for our project.*)

Alternative uses for magnesium and calcium carbonates and oxides include animal feed, water treatment, industrial manufacturing, spill response, oil and gas, construction, cement production and more. Our project will represent a significant percentage of MgO demand at gigaton scale that would not otherwise be mined.

Measurement and Verification (Criteria #4 and #5)

7. We are aware that the current state of the field may include unknowns about the kinetics of your material. Describe how these unknowns create uncertainties regarding your carbon removal and material, and what you wish you knew.

We have demonstrated the uptake rate of the material with carbonation times on the order of two weeks. However, we need to verify this under optimized real world conditions to ensure that the material uptake is sustainable at scale.

Additionally, research indicates this uptake rate can be maintained for several cycles (> 10 cycles). However, we have not tested this ourselves and are actively building out this capability. This is a key lever for cost and efficiency because the longer that we can maintain the materials carbon uptake capacity and rate, the less extractive the process is and the lower the process cost can be.

8. If your materials are deployed extensively, what measurement approaches will be used to monitor weathering rates across different environments? What modelling approaches will be used, and what data do these models require?

We expect to have a model of the carbonation as a function of different conditions and the number of cycles. At this stage, we can take spot-measurements of different racks which allows us to determine the carbon content and carbonate species to corroborate the model and ensure nothing is off within the process. We can measure the amount of CO₂ in the material using total carbon analysis, which allows us to perform these spot measurements. Additionally, there are chambers that provide instantaneous CO₂ flux readings that can be adapted for large scale CO₂ uptake monitoring.

Human and Ecosystem Impacts, Toxicity Risk (Criteria #7)

9. What are the estimated environmental release rates of heavy metals (e.g. Cr, Ni, Pb, Hg)? Dust aerosol hazards? P loading to streams? How will this be monitored?

There are no estimated heavy metal emissions. However, we are using fine powders, which are produced from the calcination process. This will require an integrated materials handling system that minimizes the dust formation after calcination, as well as during the carbonation step. This can be monitored in a series of different ways, many of which are already in practice at large cement companies and include personal protective equipment, dust extractors and filtration devices.

In our process, we expect to limit the amount of dust exposure via a carefully designed materials handling system and engineered methods to reduce the aerosole potential of the materials.

10. If minerals are deployed in farmland, what are the estimated effects on crop yields, what's this estimation based on, and how will actual effects be monitored?

The minerals are not being deployed on farmlands.

11. How will you monitor potential impacts on organisms in your deployment environment? (E.g. Health of humans working in agricultural contexts, health of intertidal species, etc. depending on the context of deployment)

We are currently monitoring the potential impacts to human health on the lab and demonstration scale, and abide by all OSHA safety requirements. We will continue to evaluate and measure our impact on human health at all scales of deployment. Additionally, in our search for a commercial plant site we will work with local biodiversity and environmental experts to ensure that our process has a limited impact on the surrounding ecosystems.

12. If you detect negative impacts, at what point would you choose to abort the project and how?

It is too early at our current scale to establish a framework or decision process for when we would abort the project. That said, we will be proactive in monitoring our negative externalities at every scale of deployment. If the process is found to have severe negative impacts, we will halt operations until we can root cause the issue and remedy the situation. We will establish mitigation pathways before beginning operations again.