

# Travertine Tech

## Carbon Removal Purchase Application

### General Application

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

Company or organization name

Travertine Technologies, Inc.

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

Boulder, CO, USA

Name of person filling out this application

Prof. Laura Lammers

Email address of person filling out this application

[REDACTED]

Brief company or organization description

Travertine Tech mineralizes CO<sub>2</sub> from the air during industrial chemical production  
*<10 words*

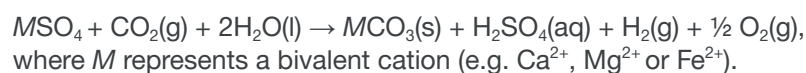
#### 1. Overall CDR solution (All criteria)

- 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 and system schematics.

Travertine Tech has developed an electrochemical process for producing and recycling sulfuric acid while simultaneously removing carbon dioxide by precipitating carbonate minerals.

The inputs to the process are a source of sulfate (e.g. calcium or magnesium sulfate),  $\text{CO}_2$  from the air (without pre-concentration), and renewable electricity. Products of the reaction are sulfuric acid, carbonate minerals, hydrogen, and oxygen.

The overall chemical reaction for the process is:



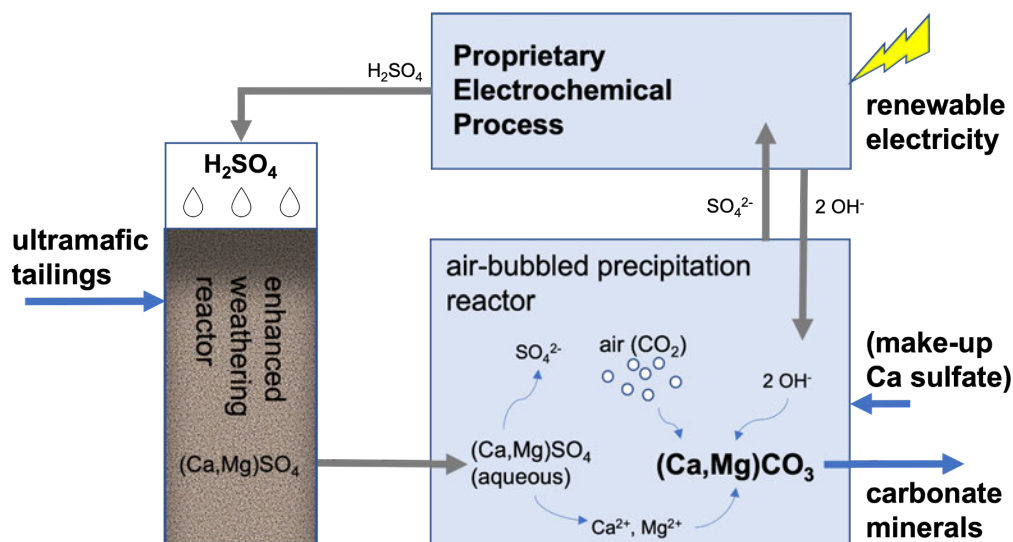
Sulfuric acid is the most used inorganic chemical in the world (300+ Mt/yr), and the sulfuric acid produced in Travertine Tech's process can be used for a number of industrial applications relevant to decarbonization:

- Leaching lithium-bearing claystones to produce lithium for batteries
- Leaching ultramafic mine tailings to extract transition metals needed for batteries (e.g. Nickel, Cobalt, etc.)
- Producing phosphate fertilizers

The long-term goal of Travertine Tech is to make CDR economically viable without needing a price on carbon by enabling the co-production and sale of valuable materials (lithium, nickel, fertilizer etc.). As a first pilot, we are building a plant that focuses solely on CDR.

Travertine Tech will be building a pilot-scale electrochemical reactor to produce sulfuric acid and mineralize  $\text{CO}_2$ . The pilot will be on-site at a mine with ultramafic tailings so that the sulfuric acid can be neutralized while enhancing weathering of existing tailings. This pilot will allow us to test a scaled-up electrochemical reactor and focus entirely on efficient CDR.

Schematic of the electrochemical reactor process is below:



The planned capacity of the pilot is as follows:

- CO<sub>2</sub> Removal: 1 t/day
- Carbonate Mineral Production: 2.7 t/day as anhydrous (Ca,Mg)CO<sub>3</sub>
- Sulfuric Acid Production: 2.2 t/day

Operation of the plant:

- Projected Start of Operation: April 2023
- Projected End of Operation: April 2024
- Projected Total CO<sub>2</sub> Removed in 1 year: 365 tons

Site Location: We are in early conversations and outreach with a number of domestic and international mining sites that meet our criteria for this pilot. We have not yet chosen a site.

<1500 words

- 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 CO<sub>2</sub>. DAC Company pays Injection Company for storage and long-term monitoring.)*

Travertine Tech's process mineralizes CO<sub>2</sub> directly from the air without pre-concentration while co-producing sulfuric acid.

The acid produced in our process will be used by mining partners to enhance the weathering rate of ultramafic tailings. Future partners could represent a number of industrial sectors (e.g., metals extraction, fertilizer production, etc.).

<50 words

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

1. **Scale-up:** Travertine Tech's process has been proven at the bench-scale, but we need to scale it up to 1 tCO<sub>2</sub>/day for this pilot and much larger for commercial-scale. An analogous electrochemical process is the chlor-alkali process, which has been done at the industrial scale for over 100 yrs.
2. **Low-cost renewable energy:** Our electrochemical process requires energy, and sourcing low-cost renewable energy at remote mining sites can be challenging. However, the mining partners we have been talking with assure us that it can be done.
3. **Funding:** Funding is needed for R&D and building the pilot plant. R&D will be covered by our seed funding, and hopefully a Stripe purchase will cover the build of our pilot plant.

<300 words

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

There are patents pending for the Travertine Tech process of sulfuric acid production and recycling with carbon dioxide sequestration. We will email the PDFs.

- e. Who's the team working on this? What's your team's unfair advantage in building this solution? What skills do you not yet have on the team today that you are most urgently looking to recruit?

Dr. Laura Lammers, the inventor of this technology and CEO and Founder of Travertine Tech, is a professor at UC Berkeley with a joint appointment at the Lawrence Berkeley National Laboratory. She is a world expert on carbonate mineralization with over 30 peer reviewed publications including top journals *PNAS*, *Chemical Science*, *ES&T*, and *JCIS*. She was awarded the 2018 Mineralogical Society of America Award and the 2020 Department of Energy Early Career Award among other honors.

Owen Cadwalader is COO of Travertine Tech. He has a background in Earth Sciences and Environmental Engineering and has scaled 3 technologies and start-ups that benefit the environment from the lab to commercialization.

Together this team is perfectly equipped to scale quickly from grams per year to megatons per year carbon dioxide sequestration. We have 3 hires on deck who will be critical to helping us optimize our process and built the pilot:

- Electrochemical Engineer - Close to making a hire
- Process Engineer - Have started recruiting
- Lab Tech - Close to making a hire

## 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 2022 - Jun 2023. The end of this duration determines when Stripe will consider renewing our contract with you based on performance.</i></p>	<p>April 2023 to April 2024 (1yr)</p> <p>&lt;10 words</p>

<p><b>When does carbon removal occur?</b></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 duration (e.g. spreading olivine for long-term mineralization). Over what timeframe will carbon removal occur?</i></p> <p><i>E.g. Jun 2022 - Jun 2023 OR 100 years.</i></p>	<p>CO<sub>2</sub> is removed from the air and mineralized while the plant is operating.</p> <p>&lt;10 words</p>
<p><b>Distribution of that carbon removal over time</b></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>Evenly throughout time, at a rate of 1 ton CO<sub>2</sub>/day.</p> <p>&lt;50 words</p>
<p><b>Durability</b></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>100,000+yrs. Carbonate minerals persist when not destabilized by calcination or acidification.</p> <p>&lt;10 words</p>

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

As long as the carbonate minerals are not acidified, they are stable at the land surface.

*Number/range*

- 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.*)

Carbonate minerals are extremely recalcitrant and can persist for hundreds of millions of years.

The net carbon dioxide removal from carbonate mineralization depends on alkalinity balance; carbonate minerals can be dissolved and re-precipitated elsewhere but will not release CO<sub>2</sub> to the atmosphere unless acidity is added to the system.

This phenomenon is well documented in both marine and terrestrial environments. In marine settings, carbonate deposits undergo recrystallization and coarsening over 10s of millions of year timescales, but recrystallization does not result in net carbon loss (cf. *Mitnick et al., 2018*). Pedogenic carbonates accumulated in arid soils are similarly stable in terms of net carbon sequestration. Meteoric water (rainwater) can dissolve carbonate minerals at the soil surface, but unless net acidity is added to the system, the dissolved inorganic carbon re-precipitates deeper in the soil profile, or the carbonate alkalinity is exported to groundwater or surface water (cf. *Mills et al., 2020*).

References: Mitnick, E.H., Lammers, L.N., Zhang, S., Zaretsky, Y. and DePaolo, D.J. (2018) Authigenic carbonate formation rates in marine sediments and implications for the marine  $\delta^{13}\text{C}$  record. *Earth and Planetary Science Letters* 495, 135-145.

Mills, J., Lammers, L.N., and Amundson, R. (2020) Carbon Balance with Renewable Energy: Effects of Solar Installations on Desert Solar Carbon Cycle. Energy Research and Development Division Final Project Report, California Energy Commission. CEC-500-2020-075.

<200 words

- 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 durability risks of this project are minimal and carbon dioxide re-release can easily be prevented.

Addition of acidity to the carbonate minerals is the most likely pathway by which precipitated carbonates could re-release CO<sub>2</sub>. This could occur by either using the produced carbonate for acid neutralization in industrial processes or by exposing the carbonate minerals to new acidity generated by sulfide oxidation (e.g., acid mine drainage), which would make the process net-neutral in CO<sub>2</sub> emissions.

Produced carbonates can be safely stored at the land surface or sold to be used as aggregate in green cement to ensure the process is net-negative in CO<sub>2</sub> emissions.

<200 words

- 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.)*

We will perform a rigorous mass balance on carbon using several independent techniques:

1. We will determine the instantaneous net alkalinity balance of the overall process by continuously monitoring pH changes in each sub-unit process. Precipitation of carbonate minerals results in a pH drop that can be readily used to measure the mineral carbonation rate (cf. *Mills et al., 2020*).
2. We will independently confirm this mass balance by sampling carbonate sediments that are formed and performing solid characterization. Solid characterization will combine,
  - mineralogical analysis by X-Ray diffraction or other suitable spectroscopic method, and
  - measuring total solid carbonate mass fraction by mass loss upon acidification.

<200 words

### 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 <sub>2</sub> ) over the timeline detailed in the table in 2(a)
Gross carbon removal	365 tCO <sub>2</sub>
Do not subtract for embodied/lifecycle emissions or permanence, we will ask you to subtract this later	<i>E.g. XXX tCO<sub>2</sub></i>
If applicable, additional avoided emissions	None for this pilot.
e.g. for carbon mineralization in concrete production, removal would be the CO <sub>2</sub> utilized in concrete production and avoided emissions would be the emissions reductions associated with traditional concrete production	<i>E.g. XXX tCO<sub>2</sub></i>

- b. Show your work for 3(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 tCO<sub>2</sub>/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\*Y\*Z\*2 = 350 tCO<sub>2</sub> = Gross removal. OR Each tower of our mineralization reactor captures between X and Y tons CO<sub>2</sub>/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 pilot plant will produce 2.2 t H<sub>2</sub>SO<sub>4</sub>/day.

The overall reaction of our process provided in 1a and here:



where *M* represents a bivalent cation (e.g. Ca<sup>2+</sup>, Mg<sup>2+</sup> or Fe<sup>2+</sup>).

In the above reaction, 1 mol of H<sub>2</sub>SO<sub>4</sub> is produced per 1 mol of CO<sub>2</sub> removed from the air.

Therefore, a pilot plant with capacity of 2.2 t H<sub>2</sub>SO<sub>4</sub>/day x (44.01 CO<sub>2</sub> g/mol / 98.07 H<sub>2</sub>SO<sub>4</sub> g/mol) = 1 tCO<sub>2</sub>/day

1 tCO<sub>2</sub>/day x 365 days = 365 tCO<sub>2</sub>

<150 words

- 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).

1 kgCO<sub>2</sub>/yr. We are currently at the bench scale.

# metric tonnes CO<sub>2</sub>/yr

- 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 tCO<sub>2</sub> capture with T tons of sorbent.*)

The Travertine Tech technology for sulfuric acid production with mineral carbon sequestration



has been proven at the bench-scale.

Detailed data is provided in a preprint of our submitted paper and will be emailed as a PDF.

<200 words

- 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.

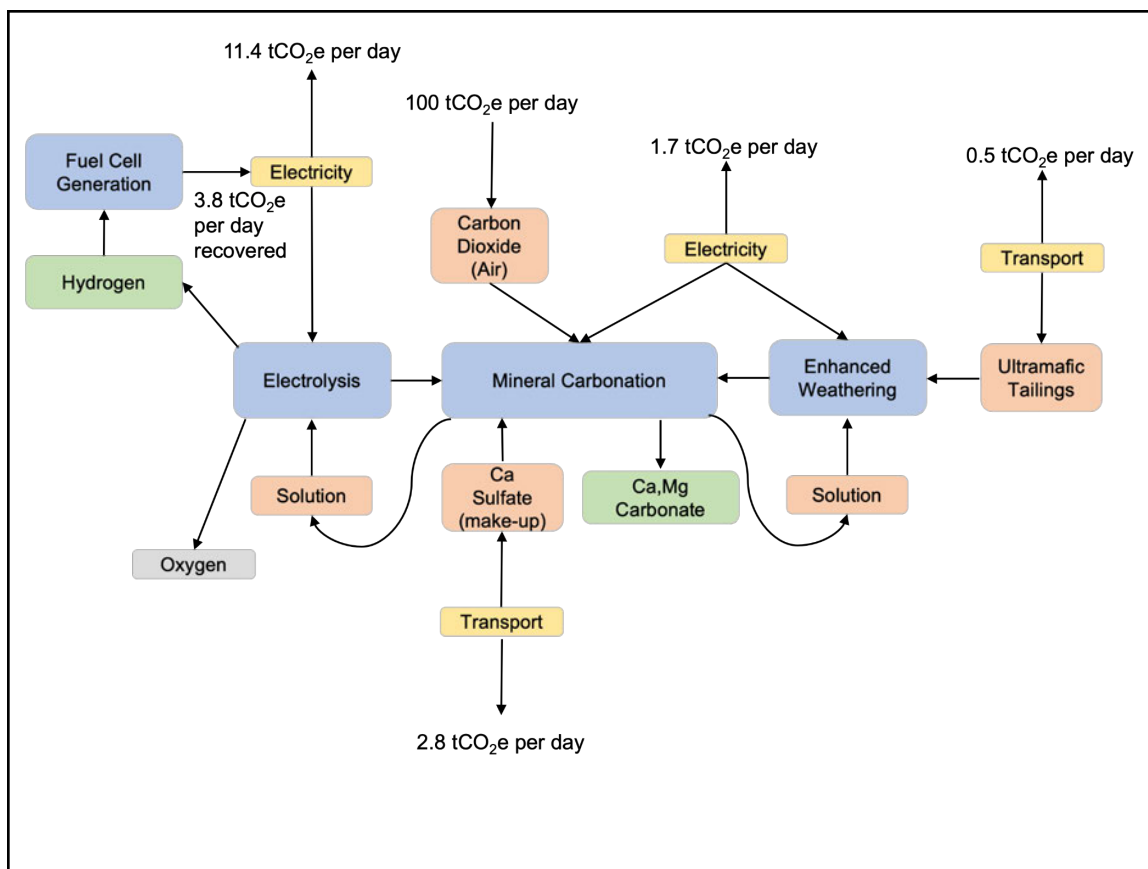
We will provide PDFs of both the pending patent and the preprint of our article describing the technology.

#### 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 <sub>2</sub> )
Gross carbon removal	365 tCO <sub>2</sub> <i>Should equal the first row in table 3(a)</i>
Gross project emissions	45.8 tCO <sub>2</sub> e <i>Should correspond to the boundary conditions described below this table in 4(b) and 4(c)</i>
Emissions / removal ratio	0.125 <i>Gross project emissions / gross carbon removal: should be less than one for net-negative carbon removal systems, e.g. the amount emitted is less than the amount removed</i>
Net carbon removal	319.2 tCO <sub>2</sub> e <i>Gross carbon removal - Gross project emissions</i>

- 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 2020 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.



- 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?

The boundary conditions of the above LCA include sequestration of carbon dioxide by mineral carbonation in an air-bubbled precipitation reactor, as well as emissions of carbon dioxide by (1) electricity required to bubble air and circulate water through the system, (2) electricity required for electrolysis, and (3) vehicle emissions associated with transporting ultramafic tailings and solid sulfate inputs.

Emissions neglected in the LCA include those associated with the manufacture and transportation of the hardware components used to construct the system. These components are expected to last many years, so we assume that they contribute negligibly to the overall carbon balance.

- 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](#).

Our LCA includes measured and modeled numbers.

Electrical energy consumption for electrolysis and air and water pumping is the main source of CO<sub>2</sub> emissions in the process. We assume a solar electricity source with 25 kgCO<sub>2</sub>e/MWh (NAS, 2018). Electrolysis is the primary consumer of electricity, and we use our measured energy intensity of 0.2 kWh/mol sulfuric acid produced in our process. We believe this is conservative, because our bench-top system has not been optimized. Electricity is generated from produced hydrogen by fuel cell, and avoided emissions were calculated assuming 60% efficiency (DOE, 2022).

Electricity demand associated with air bubbling was based on the measured rate of mineral carbonation. Electricity requirements for water pumping were estimated based on the calculated water flux necessary to maintain chemical stability in the electrochemical cell.

Emissions associated with transportation of solids were determined by calculating the maximum tonnage of tailings and solid sulfates required for equivalent CO<sub>2</sub> sequestration potential (based on 20% efficiency of carbonation of ultramafic tailings typical of the Stillwater PGM mine; Woodall *et al.*, 2021). Calculations assume that the tailings must be transported a total of 1 km to and from the system and that solid gypsum (Ca sulfate) inputs must be transported 1600 km with trucking emissions of 0.16 kg CO<sub>2</sub>/tonne-mile.

References: DOE 2022,

<https://www.energy.gov/eere/fuelcells/doe-technical-targets-hydrogen-production-electrolysis>

National Academies of Sciences, Engineering, and Medicine. "Negative emissions technologies and reliable sequestration: a research agenda." Negative emissions technologies and reliable sequestration: a research agenda. (2018).

Woodall, C.M., Lu, X., Dipple, G. and Wilcox, J. (2021) Carbon Mineralization with North American PGM Mine Tailings—Characterization and Reactivity Analysis. Minerals 11, 844.

- 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.

NA

## 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 progress.)

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

We are currently at the bench-scale.

- 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.

Year	Units deployed (#)	Unit cost (\$/unit)	Unit gross capacity (tCO <sub>2</sub> /unit)	Notes
2022	0	-	-	2022 will be spent on R&D and design of the pilot to be deployed in 2023.
2021	1	NA	1 kgCO <sub>2</sub> /yr	Bench-scale system.
2020	0	-	-	<50 words

- 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.*)

Costs have been all R&D related costs so far.

- 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 <sub>2</sub> /unit)
1	365 tCO <sub>2</sub> /unit/yr
<i>Number</i>	<i># tCO<sub>2</sub>/unit</i>

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

We are open to purchasing high cost carbon removal today with the expectation the cost per ton will rapidly decline over time. We ask these questions to get a better understanding of your potential growth and the inflection points that shape your cost trajectory. There are no right or wrong answers, but we would prefer high and conservative estimates to low and optimistic. If we select you for purchase, we'll expect to work with you to understand your milestones and their verification in more depth. [If you have any reservations sharing the information below in the public application format, please contact the Stripe team.](#)

- a. What is your cost per ton of CO<sub>2</sub> today?

\$1369/tCO<sub>2</sub>

- 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." Consider describing your CAPEX/OPEX blend, non-levelized CAPEX costs, assumptions around energy costs, etc.

This is inclusive of CAPEX and OPEX to build a pilot-scale electrochemical reactor and run it for one year:

CAPEX: \$375,000  
 OPEX (1 yr): \$125,000  
**Total Cost: \$500,000**

These numbers are from our detailed TEA for a 1 tCO<sub>2</sub>/day system. The majority of the OPEX cost is energy consumption by the electrochemical cell. We are using an energy cost of \$0.06/kWh.

Note that for a commercial purchase from this plant (not including CAPEX, without any optimization, and without sale of any co-products), CDR could be sold for \$342/tCO<sub>2</sub> to break even.

This budget does not include optimization and design that will be needed prior to building the pilot plant. Nor does it include any further R&D.

- c. How do you expect your costs to decline over time? Specifically, what do you estimate your cost range will be as you reach megaton and then gigaton scale? We recognize that at this point, these are speculative and directional estimates, but we would like to understand the shape of your costs over time.

We have completed a detailed TEA of our process showing that at commercial-scale (~1500 tCO<sub>2</sub>/day, ~3000t sulfuric acid/day), when selling sulfuric acid at current commodity prices of ~\$200/ton, it is possible to generate CDR for free (\$0/tCO<sub>2</sub>).

We expect to be able to reach commercial-scale by 2026.

- d. Where are the primary areas you expect to be able to achieve cost declines? E.g., what are the primary assumptions and sensitivities driving your cost projection? What would need to be true for a long-term cost of <\$100/ton to be achievable with your technology? (i.e., you are able to negotiate an x% reduction in CAPEX at scale and purchase renewable electricity at \$/kWh)

Our process will come down the cost curve by producing high-value products used widely in industry today, and by economies of scale. Key areas of revenue generation and cost reduction are listed below:

#### Revenue Generation

- Selling sulfuric acid for lithium mining in claystones (>\$200/tH<sub>2</sub>SO<sub>4</sub>)
- Selling sulfuric acid to extract metals from ultramafic mine tailings (>\$200/tH<sub>2</sub>SO<sub>4</sub>)
- Producing phosphate fertilizers by using sulfuric acid autocatalytically (>\$800/t MAP)
- Selling hydrogen co-produced in our process (>\$3000/tH<sub>2</sub>)
- Selling carbonate minerals as aggregate (>\$100/tCaCO<sub>3</sub>)

#### Cost Reductions

- Renewable energy price at scale (\$0.02/kWh)
- Reduction in CAPEX with economies of scale (e.g. bulk membrane purchasing)

- e. In a worst case scenario, what would your range of cost per ton be? We've been doing a lot of purchasing over the past few years and have started to see a few pieces that have tripped people up in achieving their projected cost reductions: owned vs leased land, renewable electricity cost, higher vendor equipment costs, deployment site adjustments, technical performance optimization, supporting plant infrastructure, construction overruns, etc. As a result, we'll likely push on the achievability of the cost declines you've identified to understand your assumptions and how you've considered ancillary costs. We would love to see your team kick the tires here, too.

The first commercial application we are targeting is to produce sulfuric acid for mining lithium from claystones. In this case, we would be partnering with a lithium extraction company in building a commercial-scale sulfuric acid plant. One of the advantages of our process is the ability to recycle sulfate in the leachate from the plant, a further cost-savings for the extraction

company.

In this application, the key cost drivers will be:

- Signing a PPA for renewable energy for <\$0.06/kWh
- The selling price of sulfuric acid (depending on site location, traditionally produced sulfuric acid can be >\$300/ton)
- The value of reducing sulfate in leachate (waste management can be >\$100/ton)
- If hydrogen can be compressed and sold

In a realistic worst-case scenario of the above, we would have to charge ~\$150/tCO<sub>2</sub> to make the project feasible.

In a best-case scenario, CDR would be a free byproduct of Travertine Tech's sulfuric acid production.

<300 words

- f. 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	Closing seed round	Providing capital for lab-space, salaries, R&D, optimization, design.	April, 2022	We will notify you when the round has closed and provide investor names.
2	Optimized modular Electrochem cell	We will scale from the bench to a modular and repeatable size for an electrochemical cell.  This will be the basis for our pilot system and future commercial systems	Q1 2023	We can send you specs on the finalized cell
3	Design of pilot	We will have a full-scale design of a	Q1 2023	We can send you

	system	pilot system that will be designed in parallel to the modular electrochemical cell.		the design
--	--------	---	--	------------

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	1 kgCO <sub>2</sub> /yr. <i>Should match 3(c)</i>	1 kgCO <sub>2</sub> /yr.	No Change
2	1 kgCO <sub>2</sub> /yr.	1 kgCO <sub>2</sub> /yr.	No Change. But the cell will enable building a system that can scale.
3	1 kgCO <sub>2</sub> /yr.	1 kgCO <sub>2</sub> /yr.	No Change. But the pilot design will enable us to build the pilot at 1 tCO <sub>2</sub> /day

g. 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)
1	\$1369/tCO <sub>2</sub> <i>Should match 6(a)</i>	\$1369/tCO <sub>2</sub>	No Change <i>&lt;100 words</i>
2	\$1369/tCO <sub>2</sub>	\$1369/tCO <sub>2</sub>	No Change <i>&lt;100 words</i>



3	\$1369/tCO <sub>2</sub>	\$1369/tCO <sub>2</sub>	No Change <i>&lt;100 words</i>
---	-------------------------	-------------------------	-----------------------------------

- h. 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?

We would ask Michael S. Regan (EPA Administrator) to require all metals extraction in the US to have net-negative carbon emissions.

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

Help recruit talented engineers and scientists and put money towards lobbying for policy changes that drive industry decarbonization.

## 7. Public Engagement (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 mechanisms 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 and how your project is working to follow the White House Council on Environmental Quality's [draft guidance on responsible CCU/S development](#). We recognize that, for early projects, this work may be quite nascent, but we are looking to understand your early approach.

- a. Who have you identified as your external stakeholders, where are they located, and what process did you use to identify them? Please include discussion of the communities potentially engaging in or impacted by your project's deployment.

**Mining Companies** - The mine we ultimately choose for this pilot will be an existing mine with produced tailings. We will be using the site for CDR and thus improving net emissions of the site.

**Communities Surrounding Mine** - We plan to engage with the communities surrounding the site to ensure they understand what our operations will be doing on site and the environmental benefits. We will ensure that our operations will be incremental relative to mining operations already underway.

- b. If applicable, how have you engaged with these stakeholders and communities? Has this work been performed in-house, with external consultants, or with independent advisors? If you do have any reports on public engagement that your team has prepared, please provide. *See Project Vesta's [community engagement and governance approach](#) as an example.*

We have not yet engaged.

- 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?

NA

- 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?

As we go forward with this project we will engage with the mining companies and local communities.

## 8. Environmental Justice (Criteria #7)

- a. What are the potential environmental justice considerations, if any, that you have identified associated with your project? Who are the key stakeholders?

This will be dependent on the site that is chosen. There is a long history of mines operating on American Indian lands. We will be sensitive to this issue and ensure that our impact is a net positive. Our aim is to have enthusiastic adoption by impacted communities, which will require community outreach in Tribal lands. For example, we can envision dedicating a fraction of our company profits to relevant stakeholder communities to be used at their discretion.

We will take advantage of the expertise of Dr. Lammers' colleagues at UC Berkeley (especially Prof. Elizabeth Hoover) to help develop a plan for Tribal outreach and engagement at relevant sites.

- b. How do you intend to address any identified environmental justice concerns?

Once we understand site-specific concerns we will develop a plan to address them.

## 9. Legal and Regulatory Compliance (Criteria #7)

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

We have not yet solicited any legal opinions.

- b. What domestic permits or other forms of formal permission do you require, if any, to engage in the research or deployment of your project? 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 are not aware of any specific permitting requirements associated with implementing the proposed process other than those required by mining companies to manage their tailings.

- c. Is your solution potentially subject to regulation under any international legal regimes? If yes, please specify. Have you engaged with these regimes to date?

None that we are aware of.

- d. 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.

We will be discharging small amounts of oxygen and sulfate in our process.  
We will make sure these are under permissible limits for the jurisdiction at the site of the pilot.

- e. Has your CDR project received tax credits from any government compliance programs to-date? Do you intend to receive any tax credits during the proposed delivery window for Stripe's purchase? If so, which one(s)? (50 words)

No tax credits have been received or are planned.

## 10. 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
<b>Net carbon removal</b> <i>metric tonnes CO<sub>2</sub></i>	329.5  <i>Should match the last row in table 4(a), "Net carbon removal"</i>
<b>Delivery window</b>  <i>at what point should Stripe consider your contract complete?</i>	April 2023 to April 2024 (1yr)  <i>Should match the first row in table 2(a), "Project duration"</i>
<b>Price (\$/metric tonne CO<sub>2</sub>)</b> <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>	\$1369/tCO <sub>2</sub>  <i>This is the price per ton of your offer to us for the tonnage described above. Please quote us a price and describe any difference between this and the costs described in (6).</i>

# 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 CO<sub>2</sub> 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 CO<sub>2</sub> 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 <sup>2</sup> )
2021	0
2022	0
2023	<0.005

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 <sup>3</sup> )
2021	<1 m <sup>3</sup>
2022	<1 m <sup>3</sup>
2023	200 m <sup>3</sup>

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

1. What sorbent or solvent are you using?

We will be using aqueous solutions reacting with ultramafic mine tailings.

<50 words

2. What is its absorption capacity? (*grams CO<sub>2</sub> per grams material/cycle*)

We conservatively estimate that the carbon dioxide absorption capacity of the ultramafic tailings that serve as our terminal alkalinity sink is 0.04 g CO<sub>2</sub>/g tailings/cycle.

*Grams CO<sub>2</sub> per grams material/cycle*

3. What is its desorption capacity? (*grams CO<sub>2</sub> per grams material/cycle*)

Not applicable.

*Grams CO<sub>2</sub> per grams material/cycle*

4. 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 water used for the process will be sourced from the pre-existing water sources for ore processing at the selected mine.

*Grams CO<sub>2</sub> per grams material/cycle*

5. How do you cycle your sorbent/solvent? How much energy is required?

Water cycling is accomplished with electrical pumps and requires approximately 420 kWh/ton gross CO<sub>2</sub> sequestration.

*<100 words*

6. What is your proposed source of energy? What is its assumed carbon intensity? What is its assumed cost? 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)

We plan to source solar electricity with an estimated energy intensity of 25 kgCO<sub>2</sub>e/MWh (NAS, 2018). We assume a cost of \$0.06/kWh for this pilot.

*<100 words*

7. Besides energy, what other resources do you require in cycling (if any), e.g water, and what do they cost? 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)

Our process will require water and a small amount of sulfate material to initiate the process (this can be locally sourced gypsum for example), as well as some water and sulfate material required for make-up of losses. The make-up costs will depend on the sulfate losses in the ultramafic tailings, which we anticipate to be minimal (cf. *Hamilton et al., 2020*). Water losses are anticipated to be minimal and will amount to any residual water in the carbonate slurry as the carbonation tank is emptied.

*Reference:* Hamilton, J.L., Wilson, S.A., Morgan, B., Harrison, A.L., Turvey, C.C., Paterson, D.J., Dipple, G.M. and Southam, G. (2020) Accelerating mineral carbonation in ultramafic mine tailings via direct CO<sub>2</sub> reaction and heap leaching with potential for base metal enrichment and recovery. *Economic Geology* 115, 303-323.

<100 words

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

The water volume for the system will be approximately 10,000 gallons for the precipitation reactor and sufficient water to saturate the tailings (50% porosity; *Hamilton et al., 2020*). Assuming one tailings cycle per week, this is equivalent to approximately 17,000 gallons of water. Water will be reused from cycle to cycle with addition of make-up water to replenish any residual water that is not removed from the solid slurry.

<100 words

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

Solids are cycled approximately once per week for both the tailings and the precipitation reactor.

# cycles/day

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

The cycled water may lose some amount of sulfate by sorption to the tailings or coprecipitation with carbonates, so this will be made-up by addition of small amounts of additional sulfate salts in each cycle.

<100 words

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

Ultramafic tailings will be replaced approximately once per week.

<100 words

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.

Spent ultramafic tailings and solid precipitated carbonates will be returned to the pre-existing tailings pile. The transportation emissions associated with this are accounted for in the LCA. This is not expected to change the tailings management safety protocols already in place at the selected mining site.

<100 words

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 process combines direct air capture with permanent mineral sequestration (DACS), with an overall energy intensity of DACS of 4.6 MWh/ton CO<sub>2</sub>e at the energy intensity of acid production measured in our bench-scale test.

Realistic improvements to the efficiency of our electrochemical system to achieve ~0.15 kWh/mol sulfuric acid will make this process more efficient for DACS than other available DAC only solutions including Climeworks (<3.3 MWh/ton CO<sub>2</sub>e).

<200 words



# 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?

Our source material is ultramafic mine tailings located at a partner mining site. Gypsum or epsomite (hydrous  $\text{MgSO}_4$ ) will be used as the sulfate source, and the sulfate is recycled in the process. Gypsum is readily mined in the western US, and epsomite is produced by numerous extractive processes.

<100 words

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

Ultramafic mine tailings, our source material, are already waste products of existing mining operations.

Gypsum is already mined and produced for industrial products such as drywall. It is also a byproduct of some extraction and fertilizer production processes. Depending on location it could be obtained from those processes. The sulfate from the gypsum will be recycled in this process. Assuming 95% recovery per cycle and operation in 1M sulfate solutions, we will need approximately 64 tonnes of gypsum total for the 1 year operation cycle of the pilot.

<100 words

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.)

No additional grinding of ultramafic tailings or solid sulfate inputs is required, because tailings and sulfate inputs are fine grained and/or soluble. Because we anticipate needing a relatively small amount of sulfate inputs (~64 T/yr), transportation of sulfate inputs to the ultramafic mining site contributes negligibly (<1%) to the carbon budget for materials sourced within 550 km of the pilot. For our LCA here we assume the solid sulfate is transported 1600 km.

<200 words

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 <sup>2</sup> ) in 2021	Competing/existing project area use (if applicable)
Source material mining	<p>&lt;0.005 km<sup>2</sup> (land area occupied by the required amount of tailings to 1m depth)</p> <p><i>E.g. X km<sup>2</sup> (dedicated basalt mining facility) OR N/A (material is waste product from X km<sup>2</sup> mine)</i></p>	<p>Existing land area, already occupied by tailings</p> <p><i>E.g. Existing mine for basalt</i></p>
Source material processing	<p>NA</p> <p><i>E.g. 2 km<sup>2</sup> (manufacturing facility or mine)</i></p>	<p>NA</p> <p><i>E.g. Gravel production facility</i></p>
Deployment	<p>NA</p> <p><i>E.g. 20 km<sup>2</sup> (transportation hub + beach area)</i></p>	<p>NA</p> <p><i>E.g. Agricultural land + beach</i></p>

1. Imagine, hypothetically, that you've scaled up and are sequestering 100Mt of CO<sub>2</sub>/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 <sup>2</sup> enabling 100Mt/yr	Projected competing project area use (if applicable)
Source material mining	<p>~95 km<sup>2</sup></p> <p>Land occupied by ultramafic tailings to 10m depth. This amount constitutes ~1/3 of ultramafic tailings currently produced annually.</p>	<p>Existing land area, already occupied by tailings, so no competing use.</p>
Source material processing	<p>NA</p>	<p>NA</p>

Deployment	NA	NA
------------	----	----

5. 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.*)

The mine tailings would remain as waste piles. The gypsum inputs would likely be used as an agricultural amendment or in drywall.  
*<50 words*

### Measurement and Verification (Criteria #4 and #5)

6. 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.

Verification would be as described in the main application.  
*<200 words*

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

Not applicable. Because our process involves chemical manufacturing and recycling at centralized plants, we can directly track the total amounts of produced alkalinity and mineral carbonates. *<100 words*

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

8. 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?

Heavy metals released during enhanced weathering in this process will either be re-precipitated (e.g., as oxyhydroxides) or adsorbed to processed tailings in the tailings reactor or will co-precipitate or adsorb to precipitated carbonates in the precipitation reactor. Any residual soluble heavy metals in the leachate solution will be returned to pre-existing tailings piles. No net release of heavy metals to the environment is expected. *<100 words*

9. 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?

NA  
*<100 words*

10. 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 will leverage existing health monitoring of the mine and ensure there are no adverse effects of our CDR process.

*<100 words*

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

We do not anticipate any negative impacts, however if negative impacts emerge we would evaluate at that time in collaboration with all local stakeholders including mine operators and community members.

*<100 words*