8 Rivers Capital- Origen
Carbon Removal Purchase Application

General Application

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

Company or organization name

8 Rivers Capital, LLC / Origen Power Ltd

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

Durham, North Carolina (8 Rivers) / UK (Origen Power Ltd) and USA (Origen Carbon Solutions Inc)

Name of person filling out this application

Adam Goff, Dustin Pool

Email address of person filling out this application

[redacted]

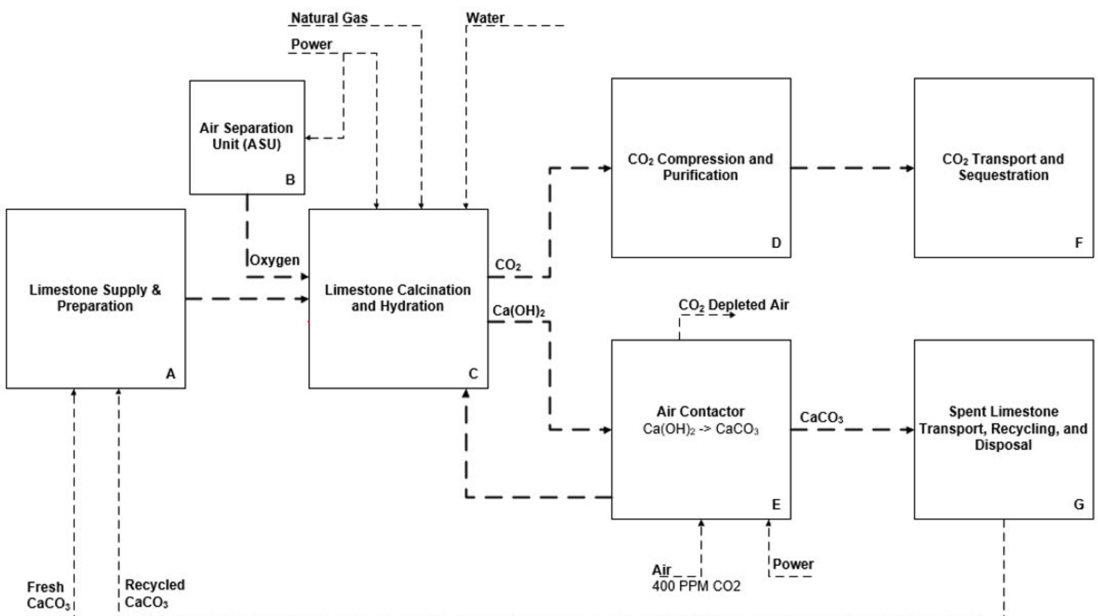
Brief company or organization description

8 Rivers invents and commercializes net zero solutions. Origen decarbonizes lime manufacturing to enable giga-tonne CO_2 removal solutions.

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 and system schematics.

8 Rivers and Origen will bring together their respective technologies for creating zero carbon lime (Origen) and using it to remove CO2 (8 Rivers's Calcite system) to collaborate on a carbon dioxide removal plant in the UK to remove 1,700 tonnes (gross) of CO2 from the air and pilot the scaled-up integration. This project would utilize Origen's existing pilot kiln integrated with the Calcite system for a one year pilot run, for fastest deployment and de-risking and to establish a basis for future larger scale joint developments. This application is independent of the proposed larger-scale Origen standalone project which will have a long-term commercial lifespan and later deployment timing.



The lime cycle creates an attractive route for scalable, low-cost carbon dioxide removal: (i) calcination of limestone ($CaCO_3$) into quicklime (CaO) and pure CO_2. (ii) Compression, transportation and geologic sequestration of CO_2, durable for >1,000 yrs, (iii) use of zero-carbon-calcium hydroxide (Ca(OH)2) for CO_2 removal, thereby recreating limestone ($CaCO_3$) which can be recycled into the calciner.

Step 1 – Calcination

Conventional thermal decomposition (calcination) in traditional lime kilns results in about 1 tonne of carbon dioxide emitted for every 1 tonne of lime produced. The emissions are roughly 1/4 fuel (typically coal or natural gas) and 3/4 from the process of CaCO3 + heat → CaO + CO_2. This generates a dilute CO_2 in the flue gas requiring high-cost post-combustion capture to decarbonize.

Origen has developed a new design of lime kiln which produces highly reactive lime and a high-purity CO_2 stream that eliminates the need for expensive post-combustion carbon purification and enables the lowest cost method to produce large volumes of 'zero-carbon lime'.

Origen's design is an oxy-fueled flash calciner. The design builds on two existing processes practiced elsewhere at industrial scale – flash calcination and oxy-fueled combustion. Flash calcination involves grinding limestone into fine particles and then entraining them in hot gases to achieve thermal decomposition over a period of a few seconds. In oxy-fuelled combustion, oxygen is separated from air using either a Pressure Swing Adsorption (PSA) plant or an Air Separation Unit (ASU). Combustion then takes place using this high-purity oxygen, rather than using air, so the produced flue gases have a CO_2 concentration in excess of 97% after water removal.

Origen is building a pilot-scale plant in partnership with Singleton Birch (the UK's leading lime manufacturer) capable of producing 3,000 tpa of lime and high-purity CO_2. The pilot will be online end-Q2 2022 and will demonstrate Origen's capability to produce zero-carbon lime.

Figure 2. Origen pilot project at Singleton Birch's Melton Ross site in North Lincolnshire, UK. Snapshot from live construction camera taken March 28, 2022.

Electricity is the conventional energy source for motor-driven processes such as for the compressors required for oxygen production and CO_2 pressurization, and for the grinding of limestone. When we scale up the process, Origen envisages undertaking comprehensive heat integration of the system to allow for the use of 'waste' heat to drive at least some of the compression steps involved in the production of oxygen and the pressurization of CO_2.

Chemical energy is the conventional energy source for the thermal energy required in calcination. Origen's early deployments will use CH_4 as fuel.

Stoichiometry of calcination: $3CaCO_3 + CH_4 + 2O_2 \rightarrow 4CO_2 + 3CaO + 2H_2O$

We view use of the use of hydrocarbon as temporarily acceptable within our long-term pursuit of giga-scale carbon removal for three reasons:

1. **Zero direct emissions, low net impact** - with CO2 capture there are no associated fuel or process emissions. Fugitive emissions are expected to be small relative to carbon dioxide removal volumes and will be accounted for in net removal calculations.
2. **Fuel substitution achievable in near-term with robust long-term options** – we expect CH_4 can be substituted for biogas with minimal design modification and can substantially increase the carbon negativity of the overall process. The pilot will be tested with biogas which is already accessible at the Singleton Birch pilot location. Further fuel optionality longer-term (suited for large scale) include the use of hydrogen and high-grade heat from Triso fuel nuclear small modular reactor (both are on the Origen technology roadmap).
3. **Enables faster technology deployment to go after CO_2 'now'** - using available, low-cost CH_4 allows us to accelerate scale-up of our carbon removal solution, removing as much carbon from the atmosphere as soon as possible while developing alternative fuel approaches in parallel.

Step 2 – Sequestration

Flue gases consisting of water vapor and CO_2 from the calcination of the limestone (step 1) are cooled sufficiently to condense out most of the water vapor resulting in >97% purity CO_2. The resulting gas mixture is further purified as necessary, so as to achieve the required offtake standard for sequestration. 8 Rivers and Origen then partner with a CO_2 offtaker to compress, transport and safely sequester the CO_2 permanently underground.

The site of Origen's Step 1 pilot is at Singleton Birch's Melton Ross site in North Lincolnshire. Singleton Birch is the UK's largest independent lime producer and is a member of ZeroCarbon Humber, which is itself a constituent of the East Coast Cluster enabled by the Northern Endurance Partnership (NEP). NEP aims to have operational common CO_2 transport and storage infrastructure in place by the mid-2020's that will transport CO_2 from the Humber and Teeside to secure offshore storage in the North Sea with storage capacity up to 1 billion tonnes.

In the near-term, 8 Rivers and Origen are pursuing non-pipeline options to transport CO2 for permanent sequestration prior to installation of the above mentioned transport/storage infrastructure. Currently, the most feasible option is every four days 20 tonnes of CO2 10 miles to the Port of Immingham, and transporting the CO2 by ship to underground sequestration in Iceland, Norway, or the Netherlands.

Step 3 – Carbonation to remove CO_2 from air

This project will be the first commercial deployment of the Calcite Carbon Removal process invented by 8 Rivers which uses calcium hydroxide to pull carbon directly from the air. If awarded, 8 Rivers will be working to deploy Calcite integrated into the Origen kiln pilot to deliver carbon removal in 2025.

8 Rivers invented the Calcite technology in H2 2019, and in H2 2020 8 Rivers in partnership with MIT was awarded an $810,000 ARPA-E grant that involves advancing the costing and design of Calcite. In Q4 of 2021, 8 Rivers completed its internal testing. In Q1 of 2022, a prominent National Laboratory began a 6 month validation program, where Lab scientists are conducting testing of Calcite in their lab facilities. For this Stripe application, 8 Rivers began seeking a site which would allow for a small-scale carbon negative first deployment of Calcite without the need to build a new calciner with carbon capture and storage, and in Q1 of 2022 selected Origen's pilot as the ideal host site.

Fans will pull air into a warehouse air contactor multiple stories tall, where the Calcite Carbon Removal process will utilize the Ca(OH)2 in order to pull CO_2 from the air, delivering carbon dioxide removal and locking carbon as calcium carbonate, which can then be recycled back into the kiln. The carbon will be captured by Origen and transported for permanent storage via underground injection. The lime would be trucked from the kiln to a .1 acre site for Calcite, with land use minimized by using vertical space in the warehouse air contactor. Generated calcium carbonate would be trucked back to the kiln, with a small portion of calcium carbonate sent to a disposal site to minimize calcium cycling and mitigate reactivity loss.

The Calcite technology uses a thin calcium hydroxide paste to remove CO_2 from the air at low cost with low technology risk, maximizing vertical space and reaction rate to reduce land area. 8 Rivers has experimentally demonstrated this system, showcasing carbonation in <24 hours. Calcite runs solely on the calcium cycle eliminating complexity and relying on proven components. The main components of this system are affordable and technologically available: a lime kiln with carbon capture, a slaker, a warehouse, a lime dipping and material removal system, and a material conveyance system.

The key next steps for the project are to secure carbon removal offtakes, complete testing of Calcite and of the Origen kiln, and then start Front End Engineering and Design (FEED) on Calcite. This would support raising construction equity internally and externally, with this Calcite project slated to enter operations in 2025.

This would kickstart the technologies, allowing for large-scale deployments of carbon removal projects. The combination of technologies has the potential to deliver gigaton-scale carbon removal at <$100 per tonne of carbon removal.

8 Rivers is also working to develop the second Calcite Carbon Removal facility at a promising US location which would include a newly built kiln with carbon capture. A high-potential site has been identified with suitable energy inputs and available CO_2 offtake, suitable to support

>100,000 MT of carbon removal. The project will continue to be advanced, dependent on the success of this Calcite pilot.

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_2. DAC Company pays Injection Company for storage and long-term monitoring.)*

8 Rivers and Origen are the project co-developers as well as the technology developers and licensors. The project must secure sufficient funds for development and construction. It would then pay for inputs and operations, and would receive revenue for carbon removal. The project would receive technology licenses from 8 Rivers and Origen. Origen will leverage its relationships with lime industrial partners (e.g. pilot/project site host Singleton Birch) as operators for the calcination process. The project will pay partners to transport the CO2, sequester it, and provide long-term monitoring.

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

Risk 1: Site-Specific Ambient Conditions Decrease Carbonation Performance

Risk mitigation: Evaluate humidification systems to boost the humidity in air contactor. Plant economic model takes into account lower capacity factors from decreased output due to weather conditions. Site selection efforts led to siting in an ideal location, in Kirmington UK, with average humidity of 80% and temperatures almost always above freezing, both of which are well suited for lime carbonation.

Risk 2: Calcium Hydroxide Looping

The plant will loop CaOH2->CaCO3->CaOH2 at a scale and frequency beyond what has been previously tested, which may impact carbonation kinetics unexpectedly. This looping data will be a key data output from the pilot. As a mitigation, if looping were to decrease reactivity, increased feed of fresh limestone would mitigate the issue and enable delivery of contracted carbon removal.

Risk 3: First of a Kind deployment

This will be a scale up from the previous testing and pilot scale Calcite units, which as with any first of a kind project entail risks of unexpected challenges or costs. These could be related to the material handling of the caustic material and the impact on the plant equipment, substrate management, air flow within the facility, removal of the generated calcium carbonate, baghouse operation to mitigate dust production, or some as-yet-unforeseen issue. This scale up risk will be made manageable by the testing that has been done and is being done by 8 Rivers, Origen, by a National Lab, and by the Front End Engineering Design process, which will confine the capital and operating cost estimates sufficient for project construction.

As a first of a kind pilot plant, the Origen calciner carries inherent risk of non-performance. This is mitigated by the highly experienced team (which includes Professor Barrie Jenkins, who is a world expert on kiln design, and the expertise of site host Singleton Birch who have been operating lime kilns for over 200 years). With the pilot online by summer 2022, learnings will be incorporated into the 50ktpa calciner design (FEED work at this scale has already been completed in 2019). We expect calciner deployments to occur within the lime sector 2023-2025+ to help decarbonize its production (i.e. further learnings captured to benefit this project in kiln operation), and further mitigating this particular performance risk in an integrated DAC solution.

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

- https://patents.google.com/patent/WO2021111366A1/en
- https://patents.google.com/patent/WO2020201720A1/en?oq=PCT%2fGB2020%2f050806

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?

Origen was founded by **Tim Kruger**, a world expert in CO_2 removal who founded and runs a research institute at the University of Oxford. He initiated Origen's pursuit of using the lime cycle to remove CO_2 from the air and his vision inspired the invention of the Origen oxy-fuel flash calcination design by **Professor Barrie Jenkins**. Barrie is the co-author of "Industrial Process Furnaces: Principles, Design and Operation" and is a combustion engineer with unrivaled experience in kiln design. Barrie's long-time colleague **Dr. Christine Bertrand** is a senior R&D Engineer at Origen and brings deep expertise in computational fluid dynamics (CFD) modeling that has helped refine the calciner design and will continue to be integral to further optimization leading up to this integrated operation with Origen and 8 Rivers. Tim, Barrie and Christine create an unfair advantage to Origen in limestone calcination and its use in CO_2 removal. Origen has built around its technical core to enhance technology and commercial development capabilities including key business leaders Ben Turner (CEO), Chris

Hankinson (CTO) and Dustin Pool (CCO).

8 Rivers Capital is a world-leader in inventing and commercializing carbon capture techologies, having invented the $^{8}RH_2$ process for clean hydrogen, the Allam-Fetvedt Cycle, as well as the Calcite technology. 8 Rivers helped found NET Power and raise $160M for deployment of the technology in La Porte Texas. 8 Rivers is leading marquee carbon capture projects in the UK with Sembcorp, and in the US with ADM and the Southern Ute. 8 Rivers 10-year head start in carbon innovation across sectors gives the team an unfair advantage in actually scaling innovations and bringing them successfully to market. 8 Rivers recently raised $100M in investment from Korean energy conglomerate SK Group, ensuring the team is well resourced to aggressively advance its projects and technologies.

As 8 Rivers and Origen scale their businesses, both are currently recruiting for additional engineering talent to lead and manage projects, as well as more world-class process engineers with experience and skills relevant to carbon capture.

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

a. Please fill out the table below.

	Timeline for Offer to Stripe
Project duration *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.*	2025-2026
When does carbon removal occur? *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?*	2025-2026

E.g. Jun 2022 - Jun 2023 OR 100 years.	
Distribution of that carbon removal over time *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".*	100% within the first two years of operations. Approximately evenly distributed. Exact distribution month by month will vary up and down, but average carbon removal year by year is expected to be roughly constant. Slower rates of carbonation in low humidity will lead to lower carbon removal in dryer periods.
Durability *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.*	>1,000 years assuming suitable CO2 underground storage is secured. Projects like CarbFix and Northern Lights have a track record of securely injecting CO2 for permanent storage.

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

In a well regulated and monitored CO2 Injection well, 100% of the CO_2 sequestered is expected to remain stored for well over 100 years, with none expected to be re-emitted, though over a 10,000-year time scale 2% of CO_2 may leak.

The risk that could lead to re-emission is upward migration of CO_2 through the injection well, through legacy wellbores, or through natural features. These risks will be mitigated through the permitting and monitoring process overseen.

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.)*

Those stated risks are fully considered in Alcalde et al (https://www.nature.com/articles/s41467-018-04423-1) estimating virtually no leakage over thousands of years. The six existing carbon storage wells have not leaked to date, and so Alcalde et al used historical data from the wider hydrocarbon industry, including underground gas storage and Enhanced Oil Recovery.

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 most plausible leakage pathway would be an issue in the trucking and shipping of CO_2 from the site to a distant CO_2 storage site, potentially leading to venting of some or all of the approximately 20 tonnes of CO_2 in each container. This would occur prior to the claiming of carbon removal, and such a loss would entail up to approximately 2% of annual removals.

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.)*

Weight measurements would calculate the amount of air-generated $CaCO_3$ vs. mined $CaCO_3$ is fed into the Origen kiln. CO_2 flow meters would calculate the amount of CO_2 captured, transported, and eventually injected, directly measuring daily carbon removal. The selected storage partner would monitor the injection sites. Measurements of air entering the air contactor and CO_2-depleted air leaving it would further validate the CO_2 flow-meter data.

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	1,711 tonnes
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 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_2/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_2 = Gross removal. OR Each tower of our mineralization reactor captures between X and Y tons CO_2/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)*

2,700 tonnes of CaO produced by Origen is estimated to contain 95% available lime. For a pilot plant, 85% carbonation of this calcium oxide in the Calcite system is projected, leading to 1711 MT of carbon removal. We have allocated Stripe 100% of this carbon removal from the first 12-18 months of operations.

2,700 MT * .95 availability * 85% carbonation * 44 MT CO2 / 56 MT CaO = 1,711 MT CO2

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).

Calcite has no existing plants, so has no capacity for carbon removal at this time.

Origen has the in-construction kiln previously described at 3,000 tonnes per year capacity.

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_2 capture with T tons of sorbent.)*

We assume the calcium hydroxide in the air contactor reaches 85% of its maximum carbonation capacity in less than a day. Our lab testing on both industrial-grade calcium hydroxide reached this speed and carbonation rate in ambient air.

Our experiment program in the second half of 2019 was weight based, with carbonation in ambient air, measurement of ensuing weight gain, with heating of the generated calcium carbonate to remove water at the end of the experiment. Our experimental program in the second half of 2021 utilizes measurements from tests in a fixed CO_2 environment, where carbonation could be tracked hourly by the flow of CO_2 into the experiment. The scale of these experiments was such that multiple grams of CO_2 could be absorbed in each test. A prominent US National Lab is completing an ongoing larger scale demonstration tests on calcium hydroxide to complete in mid-2022. Their initial small scale validation tests have shown similar carbonation rates and carbonation maximums, measured by Thermogravimetric Analysis (TGA), and further validating the 8 Rivers lab results.

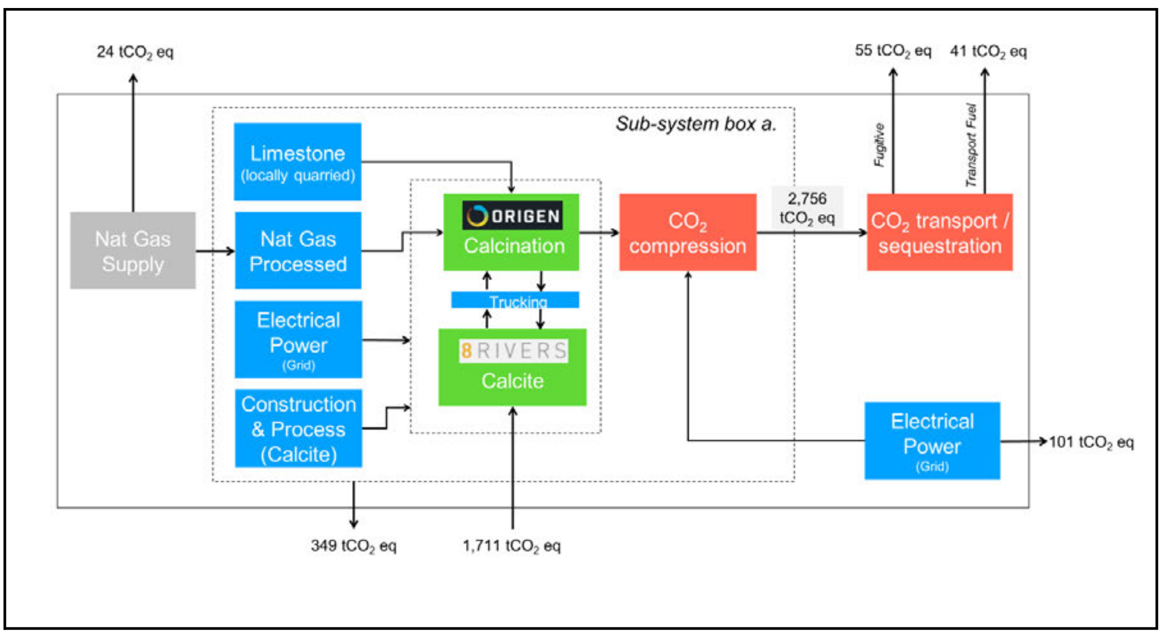
e. Documentation: If you have them, please provide links to any other information that may help us understand your project in detail. This could include a project website, third-party documentation, project specific research, data sets, etc.

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	1,711
Gross project emissions	570
Emissions / removal ratio	.33
Net carbon removal	1,141 MT CO2

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.



The above diagram represents a 1,711 tCO_2 gross removal system through the cycle described in 1a. Life cycle analysis on the components within 'sub-system box a.' in the diagram indicates that 349 tCO_2 eq will be emitted for every 1,711 t CO_2 eq removed with the combined Origen calcination and Calcite carbonation process. The 349 tCO_2 eq is broken down into 128 tCO_2 eq for electrical power in Origen calcination, 52t CO_2 eq for CH_4 and CO_2 fugitive emissions in calcination, 163 tCO_2 eq from Calcite embedded carbon of construction and process materials amortized over the short 1-year asset life, and the remaining 6 tCO_2 eq from trucking of limestone and lime between calcination and carbonation sites.

To be conservative, we assume the carbon footprint of grid electricity remains at 2018 levels at our proposed site in the UK. Any improvements in the carbon footprint of the available grid would reduce the associated carbon footprint of this described process.

Outside of the 'sub-system box a.', we estimate the impacts of natural gas supply, CO_2 compression equipment and fugitive emissions from CO_2 transport/storage infrastructure.

Based on a fugitive emission estimate of 2.9% in the UK (Boothroyd et al, 2018), we calculate 24 tCO_2 eq annualized emissions as shown in the diagram above. While we have used natural gas in our net capacity calculations for conservatism, we are in the process of evaluating a switch to biogas, to be completed by the time of our project with Stripe (there is already an anaerobic digester at the pilot site and biogas use is included in the testing program of the pilot calciner in 2022/23).

For CO_2 transport/storage, we assume a conservative 2% fugitive emissions associated with the 2,756 tCO_2 eq represented by the 55 tCO_2 eq shown in the diagram. A further 41 tCO_2e is estimated for trucking and shipping. These figures are our estimates and will be refined as we select a CO_2 sequestration partner and further examine the CO_2 transport solution.

A CO_2 compressor is expected to be leased. The electrical power impact is based upon the same 2018 UK grid electricity and ratio of power required vs our calciner from 2019 FEED work conducted (presentation to UK government attached), resulting in an additional 101 tCO_2 eq reflected in the diagram.

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 boundaries of this analysis are the Scope 1, 2, and 3 emissions of the Origen and Calcite facility, from embodied emissions in raw materials, to power use, to trucking miles during operations. All major components are included to our knowledge. Some amount of raw materials in the balance of plant have not been included, as we have not yet completed FEED and so do not know their quantities, but the CO2 impact is expected to be minor.

Because this is a pilot facility expected to have a limited commercial life, it is conservatively assumed that the facility ceases operating after delivering carbon removal to Stripe. As a result, construction emissions and embodied emissions from the purpose-built Calcite plant, which are usually spread across many years of operations, are quite concentrated. Were the facility to operate for 5 years rather than 1 year, the construction and material emissions would decrease 5x.

Additionally, construction emissions of pre-existing equipment (kiln, slaker, pipelines, etc.) are not included in this LCA since those pieces of equipment are already constructed and would not change whether or not this project was built to deliver carbon removal to Stripe.

Note: we have not yet included the carbon footprint of the limestone source material e.g. electrical consumption for quarrying and conveying at the Singleton Birch plant. A figure of 6kWhr/tonne is quoted in Ellerbrock and Mathiak - ZKG vol11 1994 page E296 - which for our pilot plant (3,000 tpa capacity) would equate to ~18MWhr/year or about 1.5% additional electrical power describe in 'sub-system box a.' and an additional 2.1 tCO2 eq in a 1000 tCO2 gross removal system and thus would have minimal impact on overall emission-to-removal ratio. We will confirm these figures in future detailed, 3rd party verified LCA work.

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](#).

All of the numbers in the above diagram are based on the project's models and assumed CO_2 intensities for inputs, using 8 Rivers experimental data and vendor data where possible. They will continue to be refined during detailed engineering and further testing. Only the carbonation of calcium hydroxide has been measured directly, in a lab setting, and further such experiments are ongoing. The numbers utilized have not been independently measured. Where possible, industry standard life cycle analyses have been utilized, such as: 1.5 kg CO2e per kg of plastic, 1.8 kg CO2 per kg of steel, 161.8 grams CO2 per ton-mile of trucking.

Fugitive emissions for natural gas and CO_2 and compression scope 2 and 3 emissions are based upon literature or conservative estimates until our FEED-level LCA is complete for the full-system.

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.

An independent verifier could review all of the raw materials inputs from the FEED study, as well as the operations plan and generated test data of carbonation, to validate the numbers provided ahead of construction. During plant operation, CO_2 flower meters at the point of CO2 capture, CO2 transport, and CO2 injection, along with CO2 monitoring at the inlet and outlet of the warehouse air contactor will provide real time measurement of carbon removal, and compositional analysis of the lime before and after carbonation could provide further validation of carbon removal.

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)

Our unit of deployment is each Calcite facility, engineered, financed, and constructed as a unit, consisting of an air contactor and an Origen kiln system. The carbon removal capacity of each facility will vary and is expected to increase with the number of deployments.

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_2/unit)	Notes
2022	0	N/A	N/A	*Calcite testing at National Lab.* *Origen cacliner pilot under*

			construction, operational mid-2022
2021 0	N/A	N/A	*Caclite: ARPA-E grant funding received. Testing at 8 Rivers. Cost modeling.* *Origen calciner pilot commenced construction*
2020 0	N/A	N/A	*Calcite testing and modeling* *Origen secured calciner pilot opportunity at Singleton Birch site in UK*
2019 0	N/A	N/A	*Calcite invention and testing* *Origen grant funded FEED study for 50 ktpa calciner*

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.*)

Through experimental testing and process optimization and cost modeling, our projected costs have declined significantly as we have increased the rate and extent of carbonation, while also improving the fidelity of these cost estimates, as we receive vendor quotes for key pieces of equipment, find ways to increase the carbonation rate, and reduce material inputs and capital costs. Continued engineering and testing during FEED will continue this process. Our internal cost modeling projects that a next-of-a-kind Calcite facility would capture carbon for below $100 / MT net CO2 removal.

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)
1	1,711 tCO2 capacity per unit

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_2 today?

Approximately $1,000 / ton CO2 net removal at pilot scale, assuming a standard levelized capital recovery factor. This modeled cost is specific to a first of a kind Calcite deployment at pilot scale, with significantly increased costs due to small scale and short plant lifetime, dominated by the labor cost of operating the plant due to its small scale.

Our modeled cost for an initial unit at large scale with a 20-to-30-year lifecycle at a US-based location is projected at below $300/ton.

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.

These costs include the cost of operating the Origen kiln and construction and operating the Calcite system. Costs for transport and storage of such small volumes of CO2 on a 12 month basis are still being estimated, and so are not included. Costs for kiln construction are not included, as the kiln was built prior to the project.

The Levelized cost is thus 17% from CAPEX, with vendor quotes and internal estimates used to cost most major pieces of equipment, and standard factors applied to calculate "Total As Spent Cost" from "Total Equipment Cost", with a Levelized Capital Recovery Factor.

Levelized cost is 83% from OPEX, including power, water, gas, material inputs, O&M, and labor costs. The energy inputs are electricity, which is assumed to cost $125 / MWH and gas, which is assumed to cost $10.5 / mmbtu. The project will explore approaches to lower the cost and CO_2 intensity of purchased electricity. The vast majority of the cost is labor cost for operating the plant, which has an outsized impact due to the small net carbon removal per year and the requirement for full-time operators of the kiln and air contactor. This is an artifact of the pilot scale and these costs will cease to be significant for full-scale facilities.

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 expect our initial plants at 100,000 ton carbon removal scale to have a levelized cost of carbon removal below $300 per ton.

At megaton scale, these costs are projected to decline to below $200/ton.

Well before reaching gigaton scale, costs are projected to decline below $100/ton. At these low capture costs, “external” variables, such as the cost and emissions of external energy inputs for calcination and the cost of capital play a large role in decreasing costs further.

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 $y/kWh)

To reach below $100 per ton, there are three key areas driving cost declines.

1. Performance: Increases in the average carbonation rate from 85% to over 95% increase the net DAC rate by 11% for the same infrastructure and energy input, proportionally reducing all other costs. Increases in the speed of carbonation reduces the size of the air contactor and the associated materials. Optimizations in the recycling of lime reduce limestone mining costs, limestone disposal costs, and the associated emissions while also maintaining lime reactivity.
2. Capital Costs: capital costs are projected to decline 50% from the first plant to the Nth of a Kind Plant. First this is driven by decreasing contingency, owner’s costs, financing costs, and cost of capital, as plants scale up and technical and commercial risks are mitigated. Second, scaling and learning effects and improved engineering reduce the cost of key equipment such as the oxy-kiln, the CO2 compression and purification equipment, and the air contactor. The air contactor accounts for 20% of CapEx, the oxy-kiln for 30%, CO2 compression and purification for 17%, oxygen

production for 10%, and the remainder is balance of plant.

3. Operating Costs: Increased scale, decreasing capital costs, and learning by doing reduces the cost of plant operation and maintenance. Improved looping reduces the cost of limestone feed and disposal. Improved oxy-kiln design increases energy efficiency and supports integration with zero-carbon sources of heat and power. Locating plants in areas with low cost zero carbon energy further reduces costs. As capital costs decline, energy costs eventually reach 50% of the levelized cost of DAC.

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.

In a worst case scenario, the cost of Direct Air Capture would range from $300-$400 / ton as opposed to the above cost projections. This could be driven by drastically increased basic materials costs for steel, cement, and plastic, alongside rapidly increasing costs for fuel and power and labor. If the cost of financing for DAC plants is high, this would magnify the impact of high equipment costs. Further, if reliable low carbon electricity becomes more expensive over time, in concert with rising natural gas prices worldwide (with no fuel switch option developed for the kiln), these combinations could lead to the worst case scenario for costs.

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	Deliver the 3,000 tpa calciner at UK pilot site and complete Phase 1	Demonstrates capability to produce Origen zero-carbon lime -	Construction completed and commissioned by end Q2 2022	Physical visit to the pilot site, photos/videos and reported

	of operations testing program	the critical first step to our carbon dioxide removal solution. Improves understanding of slaked flash calcined lime characteristics and enables performance testing with 8 Rivers contactor	Phase 1 operational testing program complete in Q4 2022 (slaked lime production may not be until H1 2023)	results of our operational testing.
2	Air Contactor Testing Complete	Further testing of the alr contactor components on Origen-produced lime, in varying conditions, at larger scale and performed by a National Laboratory all will provide critical data and validation for the successful design, financing, construction, and operation of the pilot plant and future full-scale plants.	Q4 2022	Review the data and outputs of the air contactor testing
3	FEED start and FEED completed	Front End Engineering and Design will significantly advance the engineering and cost estimation of this Calcite project, and learnings will also be applicable to	Q4 2022 start. Q4 2023 finish.	Verify that signed contracts have been obtained from an appropriate FEED vendor and receive confirmation that work has begun.

		future Calcite projects. It will generate a cost estimate with sufficient accuracy and detail for an EPC contract.		Verify the completion of FEED.

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	0 MT CO_2	0	N/A
2	0 MT CO_2	0	N/A
3	0 MT CO_2	1,711 MTPA gross CO_2 removal once construction is complete.	Completion of construction based off of FEED will start the operations of the first Calcite plant in 2025, which has 1,711 MT gross carbon removal capacity as previously described.

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

Milestone #	**Anticipated cost/ton prior to achieving milestone (ranges**	**Anticipated cost/ton after achieving milestone (ranges are**	**If those numbers are different, why? (100 words)**

	are acceptable)	acceptable)	
1	*<$1,000 / ton*	*<$1,000 / ton*	*N/A*
2	*<$1,000/ton*	*<$1,000 / ton*	*N/A*
3	*<$1,000/ton*	*$500 - $1,500 / ton (Calcite at pilot scale)* *<$300 / ton (Calcite modeled at 100k / ton scale)*	*During FEED, costing accuracy will be improved with AACE Class II/III budgetary estimate. This will lead to a new cost estimate that could be lower or higher than the current Class V estimate, hence the range given.*

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?

Ask United CEO Scott Kirby (or equivalent carbon removal market leader) to agree to purchase terms for the first 10 million ton of carbon removal from Calcite projects, enabling rapid acceleration of the project development cycle to build large scale carbon removal plants.

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

Help introduce us to other potential carbon removal offtakers

Help to identify potential carbon removal project equity investors interested in funding development and our construction of multiple Calcite facilities

Continue to lead and grow the carbon removal ecosystem

Support federal policy improvements that support carbon removal, such as 45Q enhancement and threshold removal.

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.

Our most active external stakeholders are mainly business (lime industry and organizations needing to decarbonize e.g. Singleton Birch in the UK), academic (e.g. point-source capture pilot-rig at Heriot Watt and Cranfield University) and the investment community (government grant BEIS / IETF, US DOE and ARPA-E, private and institutional). Our day-to-day external stakeholders are then local and national trade media, government (BEIS and US DOE), our direct suppliers (legal, MarComs), our colleagues, supply chain partners (design, electrical and mechanical engineering) and future commercial collaborators both national and international. These groups have been developed over time as the project has transitioned from design to implementation and as funding rounds have developed. For our pilot oxy-fuel flash calciner, we have leveraged our partnership with Singleton Birch ("SB" as host of our pilot) and their existing relationships with the local community in North Lincolnshire, UK. SB works closely with local industry training provider CATCH, The University of Hull, Engineering UTC North Lincolnshire, and Ridings School. At all these establishments SB has either a member on the board or a designated liaison individual. SB puts all its operators through NVQ's, from level 2 to 5 depending on job role, and use several local training providers. SB uses KTP (Knowledge Transfer Partnerships) with Hull University to get skilled graduates within the business. They also work with schools through our reach-out programs, sessions with GCSE and A-Level students focus on the lime-cycle and Singleton Birch's carbon emissions, as well as the novel work we are doing to promote carbon reduction particularly around our zero-carbon lime pilot plant. SB also lectures at the University of Hull on these topics.

For the development and piloting of Calcite at lab-scale, 8 Rivers collaborated with MIT, ARPA-E, and a prominent National Laboratory.

As the project develops in the UK, we expect to welcome greater civil society, government, and media interest – mainly associated with the building of the DAC plant. As such, to enable us to map the developing compliance, legal and environment landscape and engage productively with the relevant stakeholders, we have engaged with an agency to identify other external interested parties. The objective will be to develop a process and methodology for engaging stakeholders and disseminating meaningful information. In addition, project specific external stakeholders will be identified in conjunction with the FEED phases for the proposed carbon removal facility.

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.*

To date, this has mainly been performed in-house, through the use of external consultants and through the evolution of the project. As mentioned above, we have leveraged our partnership with Singleton Birch (as host of our pilot) and their existing relationships with the local community in North Lincolnshire, UK.

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?

8 RIvers' engagement with stakeholders led to a renewed focus on looping the generated CaCO3 to reduce costs as well as mining land use and associated impacts.

Origen's original work in this space considered the use of lime for CO2 removal through enhancing ocean alkalinity. While such an approach is more technically efficient - removing almost double the amount of CO2 as recarbonating lime on land - stakeholder engagement informed us that adding lime to seawater is too socially contentious at this point in time to be deployable. While we have not completely abandoned the pursuit, we have deferred the position/priority of zero-carbon lime use in ocean alkalinity enhancement accordingly on our technology roadmap and refocused the business on 1) decarbonizing lime manufacturing, 2) leveraging that capability toward direct air capture solutions.

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?

> Origen and 8 Rivers will take a proactive project-by-project approach to stakeholder identification and management. In early deployments, Origen and 8 Rivers will co-develop projects with industry and continue to leverage existing long-standing relationships with local communities. Those learnings will be incorporated to larger scale carbon removal operations in which Origen and 8 Rivers are more likely to be taking a lead or primary role in stakeholder management.

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?

> Increasing the productivity of already existing and well-established lime quarries by reducing wastage and the need to expand the quarry (our calciner effectively uses a waste material, ‘excess fines’, to the lime industry). Our project utilizes existing space in an industry with a finite market typically in industrial regions where high-skilled jobs are scarce and innovation is limited. The project will aim to help re-energize innovation in a region that has seen year on year decline, with industry that is based on clean technology, and with a project templated that could be scale up to further create jobs and economic opportunity. There is a very strong economic, social and environmental benefit to our technology and approach.
> In the case of deployment of our technology using natural gas chemical energy in calcination, it offers an opportunity for hydrocarbon producing countries, governments, and communities to participate in a net carbon negative solution. While Origen and and Calcite may well be fueled in the future by alternative energy sources(as described in previous sections), we see potential opportunities for bespoke deployments using natural gas to be beneficial to transitioning communities.

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

> Directly, through the planning and development phases of the pilot build we have completed the necessary Environmental Impact Assessments to enable permitting and worked with local Environment Agency and Planning Authorities to gain to correct levels of consent and mitigate

social and environmental challenges. The project is not expected to create any environmental justice concerns.

In terms of day-to-day business operations, we have plans to adopt both ISO9001 and ISO14001 to ensure a robust framework for managing both quality and environment is embedded within our processes. Our Quality Management System will be operable alongside an Environmental Management System.

By creating focus on our approach to engaging with those raising concerns by utilizing the services of a specialist public advocacy agency.

9. Legal and Regulatory Compliance (Criteria #7)

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

We have undertaken an Environmental and Social Impact Study which explores potential legal issues. With the exception of ensuring that any development achieves required planning consent, no legal restrictions on deployment were identified.

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.

Both current and potential future research and deployment of our project would be covered by existing permissions issued by the UK's Environment Agency. While we are required to inform them of any new activities, they fall under permitted development and do not require any additional permits. Ultimately, if there is storage of CO2 in the UK, it will require following additional regulations, but these have yet to be developed and those regulations will be common to all parties who are seeking to store CO2. If the storage of CO2 is in Iceland, Norway, or another country, that sequestration site will continue to follow the relevant local and national regulations.

The Singleton Birch plant at Melton Ross has operated under an Environment Agency permit for approximately 32 years without any enforcement notices and has a good relationship with the Environment Agency. Singleton Birch also operates under ISO14001 – Environmental Management system and is fully conversant with the operation and maintenance required for lime kilns as they operate 4x 600T/day Maerz kilns and have a 200-year history of operating on this site. At the planning stage of the calciner pilot, we engaged with a local Environmental Consultant who provided the permitting, planning, site and impact assessment investigation

services. An Environmental Permit has been issued for the period of five years for the Origen pilot plant.

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?

We do not anticipate our solution will be subject to international legal regimes. It is anticipated that the removal of CO_2 from the air and the geological storage of CO_2 may occur in different countries, however the cross-border shipment of small volumes of CO_2 is already common in the food and beverage industry in Europe, and it is anticipated that shipping 1,700 tonnes of CO_2 would require similar standard approvals and forms. International legal regimes might be relevant at larger scales if the removal of CO_2 and its storage occurred in different jurisdictions, or if the credits for removal were traded across borders in which case considerations relating to Article 6 of the Paris Agreement would be relevant.

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.

The precise regulations for the transport and storage of CO_2 in the UK are still in the process of being developed. Given that this is a priority for the UK Government – and an absolute necessity to achieve the legal requirement of the Climate Change Act (2008) - we anticipate that these regulations will not inhibit our ability to transport and store CO_2, particularly given the intent to ship the CO_2 internationally to already-existing CO_2 sequestration sites.

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. There are no regulatory incentives or tax credits for this project available in the UK.

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
Net carbon removal *metric tonnes CO_2*	1,100 metric tonnes of CO2
Delivery window *at what point should Stripe consider your contract complete?*	2025-2026, within the first 12-24 months of plant operation
Price ($/metric tonne CO_2) ***Note on currencies:*** *while we welcome applicants from anywhere in the world, our purchases will be executed exclusively in USD ($). If your prices are typically denominated in another currency, please convert that to USD and let us know here.*	$1,300 / metric tonne net CO_2 removal

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_2 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_2 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)
2022	.005
2023	.005
2024	≈.006

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	0
2022	0
2023	≈1,000 m^3

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

1. What sorbent or solvent are you using?

> Calcite and Origen utilize limestone, calcium oxide, and calcium hydroxide.

2. What is its absorption capacity? *(grams CO_2 per grams material/cycle)*

> 1 gram of calcium hydroxide ($Ca(OH)_2$) can absorb up to a maximum of .78 grams of CO_2. At 85% carbonation, .663 grams of CO_2 per 1 gram of $Ca(OH)_2$ would be absorbed per cycle.

3. What is its desorption capacity? *(grams CO_2 per grams material/cycle)*

> At 90% calcination efficiencies, .4 grams of CO2 per gram of $Ca(OH)_2$ would be expected

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)

> Carbonation of calcium hydroxide produces calcium carbonate. For cycling, this calcium carbonate would be collected and removed from the Calcite air contactor, and inputted into the Origen calciner with carbon capture, which heats the material to ~900°C, generating calcium oxide which then goes through a slaker to produce calcium hydroxide. Limestone is highly abundant and locally quarried in our project at the Singleton Birch UK host site.

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

> Carbonation of calcium hydroxide produces calcium carbonate. For cycling, this calcium carbonate would be collected and removed from the Calcite air contactor, and inputted into the Origen calciner with carbon capture, which heats the material to ~900°C, generating calcium oxide which then goes through a slaker to produce calcium hydroxide. Energy requirements are reflected in the LCA attachment(s) in Section 6. Heat requirements would vary by the calcining process, which as an example could require 4.9 gigajoules per ton of CaO, equivalent to 3.7 gigajoules per ton of $Ca(OH)_2$

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)

The oxy-fuel flash calciner will use both local UK grid electricity and natural gas (in early deployments) to provide the heat energy required to thermally decompose the CaCO3. We expect a cleaner electricity grid to reduce emission to removal ratio, see Section 6 and attached LCA. Longer-term, additional improvements of the carbon footprint are expected through substitution of natural gas (biogas and renewable energies) and through scale. The air contactor will use local UK grid electricity to power fans and other equipment. Transport of CO2 is expected to require diesel and bunker fuel for truck and ship transport.

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)*

Water is the other key resource, which is utilized both to mix with calcium oxide, and potentially to boost humidity within the air contactor. It is assumed to cost $1.9 per thousand gallon, but will be further explored during FEED. Water costs vary significantly by location. Water that passes through Calcite is evaporated into the air and output in the exhaust fans with the CO_2-lean air.

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

In this project, 1,042 gallons of water per gross tonne of carbon removal, primarily for making the calcium hydroxide slurry.

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

7-21 cycles per week.

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

Cycling would decrease the reactivity of the calcium sorbent, due to calcination, however due to re-hydration of lime into calcium hydroxide, lime is largely reactivated, minimizing expected reactivity loss. Currently 8 cycles per unit of lime is assumed before disposal to keep reactivity loss to a minimum however the exact number of cycles and reactivity loss will be determined during this pilot which integrates Origen and Calcite.

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

Sorbent is conservatively assumed to be replaced every 8-10 cycles to balance minimized mining with minimal reactivity loss. Future projects are expected to have a greater number of cycles of sorbent before it is replaced by fresh limestone input. This will be dictated by balancing the cost of fresh limestone versus the costs and decreased reactivity from each cycle of sorbent.

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 its life, the sorbent is disposed of as spent $CaCO_3$ into a disposal pit as part of the limestone mining complex. Disposal pits already exist in the limestone industry, used to dispose of fines, kiln dust, and other waste products. Spent $CaCO_3$ is not hazardous. Existing mine procedures ensure end-of-life safety in the disposal pit, typically related to mitigating potential dust emissions through wetting and other measures.

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.

Calcite has multiple advantages over competing technologies. It utilizes only limestone as a key input, a low cost and abundant feedstock. By relying solely on the calcium cycle, it reduces cost and complexity associated with sodium hydroxide and potassium hydroxide. Because calcium carbonate is abundant, cycling degradation can be easily remedied by fresh input of calcium carbonate when required, and by cycling through calcium hydroxide the sorbent degradation common in calcium looping is largely avoided. No new complicated components or proprietary catalysts are required by the Calcite process, as it relies on readily available equipment widely used in existing industries such as cement, lime, limestone, and materials handling, enabling a much faster scale-up and progression to next-of-a-kind costs.

The Calcite process specifically accelerates the rate of carbonation of calcium hydroxide so carbonation is complete in <1 day, which is key to reducing costs of material handling and reducing land use. The energy use of Calcite is similar to that of competing technologies, as this is driven by the energy for calcination and carbon capture. However due to its simpler low cost design, Calcite has lower capital costs and lower technical risks for large scale deployments, giving it the potential to scale quickly with financeable projects, and to achieve next-of-a-kind costs well below $100 per ton of net carbon removal.

Origen has initially focused on the manufacture of highly reactive zero carbon lime as the route to enable Direct Air Capture.

Our patented calcination technology, which is highly scalable, will consistently produce a fine highly reactive zero carbon lime. The key to rapid Direct Air Capture is the high surface area to volume ratio, a characteristic of our zero carbon lime.

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?

The source material is limestone or chalk ($CaCO_3$), which is readily available, comprising roughly 10% of the surface mineral on the planet. It can be extracted by quarrying e.g. locally in our project at the Singleton Birch host site in the UK.

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

Quarrying is part of the existing lime industry and is routinely practiced around the world. Good practice in this space involves removing surface vegetation, extracting the mineral and then replacing the surface vegetation, so that the quarrying site retains the pre-existing biodiversity. During the process of quarrying there are inevitable ecological impacts relating to noise, dust and emissions from machinery. The fact that quarrying is undertaken widely around the world in pursuit of other societal benefits indicates that properly managed quarrying can be conducted without creating countervailing side-effects. Origen partners with the lime industry to co-produce its source materials (e.g. with Singleton Birch in the UK).

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 limestone or chalk used in our process needs to be ground to around 60 microns so that it can be rapidly thermally decomposed in our kiln. The grinding is required to decrease size rather than increase surface area (the majority of the surface area is internal to the particles). The decreased size allows the thermal decomposition to occur more quickly as the rate of decomposition is inversely related to the diameter of the particles. The energy requirement and associated carbon footprint for grinding is included in the LCA.

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	<1.5 km2 (active mine at Singleton Birch supporting production of ~0.5 Mtpa lime. Source material required to service our project of ~0.003 Mtpa lime will be a fraction of this area.)	Existing Singleton Birch limestone mine
Source material processing	0.005km2 (3,000 tpa oxy-fueled flash calciner pilot footprint)	Vacant land within existing lime processing plant at Singleton Birch
Deployment	3,120 m2 including air contactor and balance of plant	Vacant land within existing lime processing plant at Singleton Birch

1. Imagine, hypothetically, that you've scaled up and are sequestering 100Mt of CO_2/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	This will depend on how many times we are able to loop the material. Single-use of lime would require quarrying of ~200Mt of $CaCO_3$ per year to remove 100Mt of CO_2. 200Mt would equate to ~0.07km^3 per year. Assuming mining to 35m this would require 2km^2 per year. If the material could be looped ten times then the land area required would be 0.2km^2 per year to depth of 35m.	Limestone is abundant. We anticipate optimal locations for the process are ones where the cost of the input materials limestone, electricity and natural gas (if still used at scale) are low and also closely located to CO_2 storage sites. While early projects may use existing lime quarries, the scale of removal required would indicate that new quarries in locations distant from current industry would be chosen. Candidate locations include desert and low population

		density areas in North America, Middle East and Australia.
Source material processing	Achieving 100 MT/yr carbon dioxide removal will require ~140 MT/yr zero-carbon lime production (assuming ~90% carbonation rate). Our optimal zero-carbon lime calcination system sizing is a 500 ktpa unit which we would then deploy modularly to achieve necessary production capacity i.e. 280 kilns. The associated land footprint of the calcination system is estimated to be 6.44 km2.	We will locate material processing equipment on vacant land adjacent to source material mining. Not seen as a creating competing pressures. Extraction and milling equipment will involve use of steel, but no exotic materials.
Deployment	On top of the above area, the air contactor system is estimated to require an additional 6.5 km2 total area for the lifetime of the facility.	Exact locations to be determined, but key candidate locations identified in North America, United Kingdom, Middle East and Australia

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.)*

Limestone is used in a wide range of applications, but its availability is so high that there is no risk of restricting supply. We anticipate at very large scales using limestone deposits that would otherwise not have been extracted.

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.

The carbonation of limestone is well understood in building material contexts, however there are significant uncertainties around the kinetics of calcium hydroxide absorbing CO2 in a

direct air capture context, in varying ambient conditions, and after repeated calcinations in an oxy-fired kiln. With better understanding of these uncertainties, as are aimed to be generated in the pilot, the Calcite and Origen system could be better optimized and deployed.

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?

Because of re-calcination of generated limestone and forced airflow inside of a closed warehouse, measurement of CO2 absorption can be completed directly via CO2 flow meters and monitoring of air CO2 inflow and outflow of the air contactor.

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?

No significant release of heavy metals is expected. Oxy-fired eliminates traditional air pollutants during combustion, as without nitrogen no NOx forms.

The main environmental hazard would be potential dust aerosol hazards particular during the processing of lime within the air contactor. Particulate Matter sensors and suitable Baghouses to reduce Particulate Matter will be deployed to monitor and mitigate this hazard.

Singleton Birch will continue their standard procedures for minimizing dust in regular operations.

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?

N/A

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)

No impacts projected, as lime is processed inside a closed warehouse to absorb CO2.

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

The project is not yet at the stage to have this decision matrix in place, however during development we will actively monitor for potential adverse impacts, proactively seeking solutions to issues before they become large problems. If a large negative impact was detected that wasn’t able to be suitably addressed and was serious enough to justify cancelling the project, the project would choose to be paused, cancelled, or modified to mitigate that negative impact.

Application Supplement: Geologic Injection

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

Feedstock and Use Case (Criteria #6 and 8)

1. What are you injecting? Gas? Supercritical gas? An aqueous solution? What compounds other than C exist in your injected material?

CO2 will be injected at the spec required by the selected sequestration partner. CO2 is to be captured in the UK, compressed into a container and trucked to the Immingham Port to be shipped to a sequestration location .

2. Do you facilitate enhanced oil recovery (EOR), either in this deployment or elsewhere in your operations? If so, please briefly describe. Answering Yes will not disqualify you.

No

Throughput and Monitoring (Criteria #2, #4 and #5)

3. Describe the geologic setting to be used for your project. What is the trapping mechanism, and what infrastructure is required to facilitate carbon storage? How will you monitor that your permanence matches what you described in Section 2 of the General Application?

To be selected

4. For projects in the United States, for which UIC well class is a permit being sought (e.g. Class II, Class VI, etc.)?

N/A

5. At what rate will you be injecting your feedstock?

2,700 tonnes of CO2 per year.

Environmental Hazards (Criteria #7)

6. What are the primary environmental threats associated with this injection project, what specific actions or innovations will you implement to mitigate those threats, and how will they be monitored moving forward?

TBD

7. What are the key uncertainties to using and scaling this injection method?

TBD