Origen

Carbon Removal Purchase Application

General Application

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

Company or organization name

Origen Power Ltd

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

UK (Origen Power Ltd) and USA (Origen Carbon Solutions Inc)

Name of person filling out this application

Tim Kruger, Ben Turner, Sam Davidson, Chris Hankinson, Dustin Pool

Email address of person filling out this application

[redacted]

Brief company or organization description

Decarbonizing lime manufacturing to enable giga-tonne scale CO_2 removal

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.

Origen leverages the lime cycle to create a route to removing carbon dioxide from the atmosphere in a way that is durable, low-cost and highly scalable.

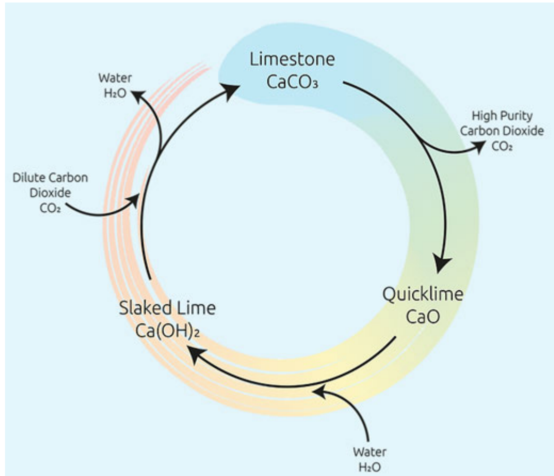


Figure 1. Origen lime-cycle. (i) Calcination of limestone ($CaCO_3$) into quicklime (CaO) or slaked lime ($Ca(OH)_2$) and pure CO_2. (ii) Compression, transportation and geologic sequestration of CO_2, durable for >1,000 yrs, (iii) use of zero-carbon lime for CO_2 removal, thereby recreating limestone ($CaCO_3$).

Step 1 – Calcination of limestone to produce highly reactive lime and high-purity CO_2

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. By separating out the nitrogen from the air, no nitrogen is introduced into the kiln (calciner) and so there is no nitrogen in the resulting flue gases. Water vapour is condensed out of the flue gases and the remaining flue gases have a CO_2 concentration in excess of 97%.

Origen is building a pilot-scale plant (see **Figure 2** below) 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, we envisage 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 a fuel.

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

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** - despite the use of CH_4 as fuel, there are no associated fuel or process emissions from its use. Fugitive emissions are expected to be small relative to carbon dioxide removal volumes and will be accounted for in any 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 our 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 of high purity CO_2 stream

The resulting gas mixture of >97% purity CO_2 (from Step 1) is further purified and compressed as necessary, so as to achieve the required pipeline standard. Origen partners with a CO_2 offtaker to safely transport and sequester the CO_2 permanently underground. We have collaborated with CO_2 sequestration companies (e.g., Vault 44.01 including joint-study mapping of sequestration potential for lime facilities across North America), to obtain high-confidence in durability, verifiability, public engagement, and cost implications of geologic CO_2 sequestration within the Origen integrated carbon removal solution.

As described in Step 1, the calcination pilot is at Singleton Birch's Melton Ross site in North Lincolnshire, UK. Singleton Birch is associated with 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 Teesside to secure offshore storage in the North Sea with storage capacity up to 1 billion tonnes. The longer-term goal of the East Coast Cluster is to be capturing and storing at least 17 million tonnes of CO_2 per year from projects across the Humber and up to 10 million tonnes from Teesside by the mid-2030s. While the exact route of the CO_2 pipeline planned for South of the Humber is yet to be confirmed, the two draft routes follow either the M180 motorway or the South Humberside Main Line railway, which both pass within roughly 1km of our pilot site. This proximity to shared CO_2 infrastructure will enable low-cost transport and storage in our project developments at this location.

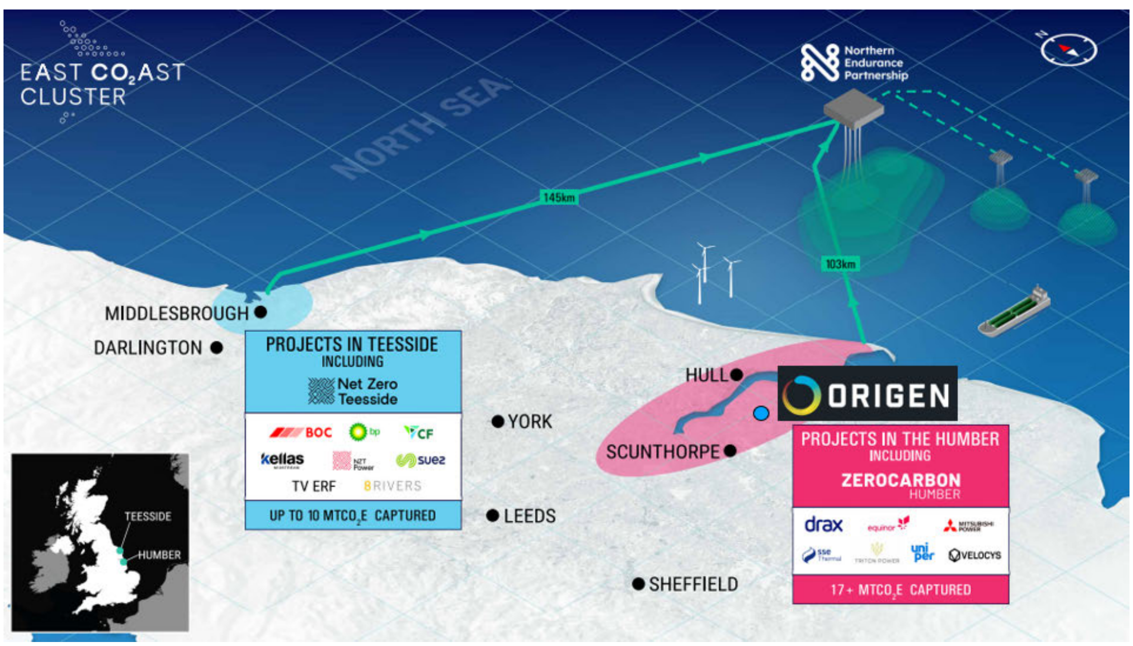


Figure 3. Map of East Coast Cluster CO_2 infrastructure with plans to collect emissions from Teesside and Humber regions in the UK.

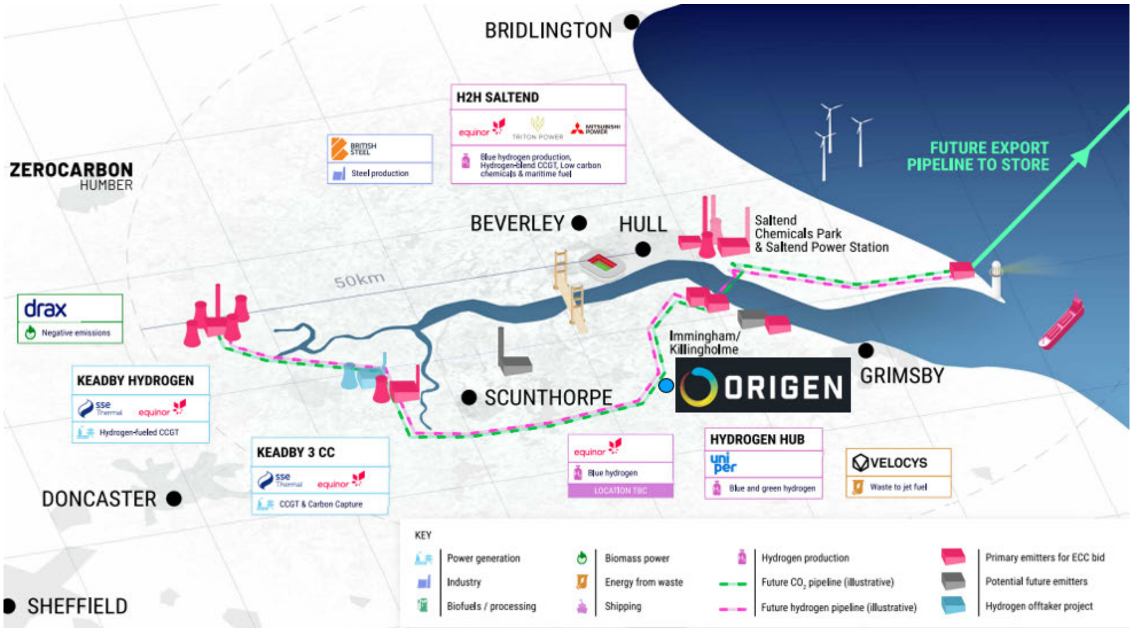


Figure 4. Map of ZeroCarbon Humber and Origen position <1km from proposed CO2 pipeline route (at Singleton Birch Melton Ross site in North Lincolnshire, UK).

Step 3 – Carbonation of lime to remove CO_2 from the air

It is well-known that lime (CaO) has a natural affinity for CO_2 - simply producing zero-carbon lime and spreading it on the ground, the lime will carbonate and, through that process, remove CO_2 from the air. In addition, Origen expects its flash calcined, fine particle size lime to have unique characteristics (more porous and highly reactive) making it an advantaged base material for carbonation.

Origen is exploring various routes of using its zero-carbon lime to remove CO_2, namely use in direct air capture (DAC) with lime-based solid sorbent, sustainable building materials (e.g., hempcrete, lime plaster), point-source capture and ocean alkalinity enhancement. We seek to partner/collaborate with other technology companies as well as developing lime-based carbonation technology/methods ourselves. We believe a combination of deployment into these carbon removal methods will lead to giga-scale removal on complimentary timescales.

This application with Stripe focuses on development of one of our DAC solutions (or ‘dynamic’ enhanced weathering) to pair with Step 1 and Step 2 for carbon dioxide removal.

Origen’s initial carbonation solution involves air capture modules that directly react fine particles of lime with ambient air. The design of these modules is a direct output of the modeling work and experiments undertaken in 2021 BEIS funded work (Greenhouse Gas Removal Phase 1) showing a method for rapid carbonation of lime in ambient air. During 2022, we will construct a module capable of removing 25 tonnes of CO_2 from the air per year.

Integration and Scale-up

With the zero-carbon lime plant online and first air capture module built (H2 2022), we will conduct a testing regime in 2023 at the UK pilot site to optimize the integration/loop between the two technologies (calcination and carbonation). Subsequently, through a model-test-design cycle, we will iterate and expand capacity to 1,000 tCO_2 per year scale by end of 2023. We will conduct initial trials with quicklime and slaked lime to determine the optimal base material considering implications to both a 'once-through' and 'looped process' between calcination and carbonation.

Following detailed design work (FEED), we will commence construction by 2025 at the current UK pilot site on a fully integrated DAC plant (capable of 31,250 tCO_2 gross removal) to be operational by 2027 (aligned with Step 2 infrastructure timing). This will be Origen's first commercial scale DAC facility that includes all three steps above and is the subject for credits to be sold to Stripe.

The initial project with Stripe will be followed by a >312,500 tCO_2 gross removal plant (size based on the optimal single unit oxy-fuel flash calciner size - 500 ktpa lime production) sited at a location to minimize costs, allow for scale and respect/support environmental justice. This unit can then be modularized / mass produced to pursue >0.5 Gt scale as a standalone solution at a cost of <$100/t by the mid-2030s.

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.)*

Origen is both the technology owner/licensor and DAC Company (developer) that owns the plant and produces compressed CO_2. Origen will contract with an Injection Company for CO_2 storage and long-term monitoring (e.g., East Coast Cluster and Northern Endurance Partnership at the UK pilot site). Origen will leverage its relationships with lime industrial partners (e.g., pilot/project site host Singleton Birch) as operators and potential co-developers of the plant.

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

Risk 1: Oxy-fuel flash calcination technology development

As a first of a kind pilot plant, the 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), further mitigating this particular risk in an integrated DAC solution.

Risk 2: Air capture module meets target capture potential and cost reductions

Simply exposing lime to air results in it carbonating with the CO_2 present at ambient temperature, pressure, and CO_2 concentration. The production of a zero-carbon lime (lime produced and the CO_2 resulting from the calcination process being sequestered) will subsequently result in the removal of CO_2 from the air, without any need for further processing other than exposing the lime to the air. The rate of the carbonation reaction can be enhanced by creating a lime that has a higher surface area, greater porosity, and smaller particle sizes (see Origen GGR Phase 1 final report). These are characteristics we expect to find in the lime we will produce from our novel approach to flash calcination, resulting in a highly reactive lime. With only minor optimizations to the air capture module design to facilitate this natural carbonation, we expect to demonstrate the required capture potential and cost reductions to achieve 0.5 gT CO_2 removal for <$100/t.

Risk 3: UK East Coast Cluster CO_2 infrastructure installed by 2027

If the UK East Coast Cluster infrastructure for CO_2 transport-sequestration were not in place by 2027, it would correspondingly delay Origen's ability to remove carbon dioxide at the proposed site in the UK. However, the construction decision (FID) for the commercial scale DAC plant (31,250 tCO_2 gross removal) will not be until end-2024 when we will know much more about the development status for East Coast Cluster (i.e., do we have confidence/commitment that infrastructure will be in place by the time the plant is operational, in 2027). The remedial action will be to relocate plans for our commercial scale plant to a location with suitable sequestration infrastructure, such as in the US, where we are already engaged with lime producers and CO_2 sequestration partners e.g., Vault 44.01 and associated joint study on geologic sequestration viability across N. America.

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

- 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 the 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 post-pilot. Christine and Barrie have also been instrumental to developing Origen's understanding of lime carbonation to date. Tim, Barrie, and Christine create an unfair advantage to Origen in limestone calcination and carbonation for use in CO_2 removal.

In the past couple of years, Origen has built around its technical core to further develop and enable commercialization of technology. Key leadership positions related to this project include:

- **Ben Turner** (CEO) - background in Earth Sciences, 10+ years investment banking & asset management.

- **Chris Hankinson** (CTO) - previously Head of Engineering at Rolls Royce's nuclear division, Chris brings significant design, technical and IP experience.
- **Sam Davidson –** (COO) experienced Operations Director in public and PE backed energy and carbon management businesses.
- **Dustin Pool** (CCO) – accomplished energy industry professional with broad background of experiences including subsurface engineering and portfolio strategy.
- **Alan Rezigh** (EVP) - 35 years in industrial project management, including broad CO_2 storage expertise.

Opportunities for zero-carbon lime are emerging rapidly. Origen urgently needs to reinforce its R&D scientist and engineering talent to accelerate and expand developments in its lime-based carbon dioxide removal technologies (including this proposed direct-air-capture technology).

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.*	**Delivery window: 2027-2028** Duration: 2027 – 2047 (usable life) Renewal: 2028 (based on Year 1 performance)
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?* *E.g., Jun 2022 - Jun 2023 OR 100 years.*	Duration: 2027 – 2047
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*	100% in first 12 months, evenly distributed over the whole time frame

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".	
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.*	Geological sequestration, permanent storage >1,000 years

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

Geological storage, >1,000 years

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.)*

Origen has already and will continue partnering with CO_2 injection/sequestration companies with proven experience/expertise in securely storing the CO_2 in deep saline reservoirs and keeping it there permanently.

Geological sequestration is considered permanent CO_2 removal, supported by the presence of naturally occurring CO_2 sources, such as the Jackson Dome in Mississippi and the Sheep Mountain pure carbon source field in south-central Colorado, and several currently operating carbon storage projects. Ultra-low permeability sealing cap rock has proven to have the ability to restrict fluid movement for millions of years and four mechanisms of trapping each play a role in preventing any migration to the surface. Durability of the project will be proven during the injection and post injection periods conducted by the Northern Endurance Partnership in the UK. Geologic storage offers permanence far exceeding the 1,000-year threshold.

https://netl.doe.gov/coal/carbon-storage/faqs/carbon-storage-faqs

https://www.denbury.com/operations/operations-overview/gulf-coast-region/co2-sources-and-pipelines/default.aspx

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?

Geologic storage reservoirs are carefully studied to mitigate physical risks of CO_2 leakage, confirmed through third party review prior to government agency certification and approval. Uncertainties are mitigated through the utilization of advanced technological methods of reservoir characterization to ensure the properties of the storage reservoir meet technical requirements. Origen's sequestration partners in North America (e.g., Vault 44.01) have unmatched technical expertise and experience to evaluate reservoirs for permanent CO_2 storage. The Department of Energy (DOE) has funded multiple CCS pilot projects to prove the safety and viability of geologic sequestration across the country, supplemented by two key projects in Canada at Shell Quest (Alberta) and Aquistore (Saskatchewan). Geologic storage is a well understood technology for permanent CO_2 sequestration. The Northern Endurance Partnership in the UK brings decades of expertise and will be actively mitigating and managing these risks.

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

The permanence and durability of geological storage will be quantified and confirmed through advanced measurement and monitoring techniques (e.g., as seen associated with a Class VI storage project in the US). During the injection period, seismic imaging, pressure monitoring, temperature logging and several other methods will be utilized to track and monitor the CO_2 within the reservoir. Once the project and injection ceases, the CO_2 plume will continue to be monitored for up to 100 years, ensuring the CO_2 is stationary within the storage reservoir. The ADM Decatur (Illinois) and Shell Quest (Alberta, Canada) projects continue to prove the viability of technological measurement techniques in quantifying the permanence and durability. These standard techniques and technology will be applied by the Northern Endurance Partnership in the UK.

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	6,250 tCO_2

embodied/lifecycle emissions or permanence, we will ask you to subtract this later	
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 *Note: We will be avoiding ~10,000 tCO_2 associated with producing the lime to enable 6,250 tCO_2 gross removals. However, if this lime would not have otherwise been produced other than for the purpose of removal, then the avoided emissions is 0 t CO_2 i.e., 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)*

One tonne of lime can remove 786 kg of CO_2 by naturally carbonating in the ambient air if carbonated fully. The European Lime Association has published a series of reports on the topic (link), see Campo et al (2021) page 4. In Origen's first commercial scale DAC plant, we will have capacity to calcine 50,000 tpa of zero-carbon lime. Given the above removal ratio, that volume of lime produced will remove 39,300 kg CO_2 if allowed to carbonate fully in the ambient air. In our process, the lime will be introduced to air capture modules to accelerate their carbonation for efficient CO_2 removal. Based on our lab work and modeling, near 100% carbonation of the lime produced is achievable. However, our conservative base case assumption is ~80%. The result is gross removal of 31,250 kg CO_2 from the 50,000 tpa of zero-carbon lime produced. The offer to Stripe is 20% of this conservatively estimated gross removal capacity to ensure very-high probability of delivery on our commitment. We expect this to account for any other broader uncertainties with technology performance or operations in the first year.

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).

At this time, Origen does not have an operating DAC plant. Our oxy-fuel flash calciner pilot is being built at 3,000 tpa (lime production) scale and is due to be operational mid-2022.

Our air capture module will be built by end-2022 to remove an estimated 25t CO_2 per annum in the first instance. We will expand capacity to 1,000t CO_2 per year by 2023 through model-test-design efficiency gains and looping tests with our pilot flash calciner. Most conservatively, if no efficiency gains and the low-end carbonation rate, 40 modules will be needed to achieve this target capacity.

With no local option for sequestration until the mid-2020s, we will not yet be removing carbon dioxide from the air with the pilot/demonstration exercises. (However, CO_2 utilization and non-geologic sequestration techniques can potentially be paired to enable the possibility of earlier CO_2 removal – this will be explored/pursued).

We will commence construction on a commercial scale DAC plant by 2025 with gross 31,250 CO_2 per annum removal capacity operational by 2027. With sequestration infrastructure in place by this time (from the East Coast Cluster and Northern Endurance Partnership described in part 1a), the plant will enable Origen's first carbon dioxide removals, reflected in 2b.

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.)*

Experimental work conducted by Origen in 2021 (Greenhouse Gas Removal Phase 1) indicates that a layer of hydrated lime of between 0.5mm and 1.5mm will carbonate over the course of a day. Our lab and modelling work explore the relationship between the time to carbonation and the diameter of the particle size, namely that the time to carbonation is inversely proportional to the square of the diameter of the particle. That is to say that if particle x is one-fifth the diameter of particle y then particle x will carbonate in one-twenty-fifth of the time that particle y would take to carbonate. Link to final report data, results, conclusions.

Based on the above experimental work, Origen's initial air capture module has been sized and designed using a hydrated lime at an optimum particle size experimental work and at the most conservative carbonation rate (link to additional basis for design and detail). It should be noted that there is still considerable uncertainty as to the rate of carbonation for the lime produced from the flash calcination kiln process that is being commissioned Q2 this year. It is anticipated that it will be highly reactive lime with a much larger surface area to volume ratio than a conventionally produced lime. We plan to test carbonation performance of the flash calcined lime as quicklime and slaked lime. With those results, we will refine the air capture module design and expand to 1,000t CO_2.

Further to our description in 2b, we will construct a 50,000 tpa oxy-fuel flash calciner and deploy the air capture modules efficiently to capture gross 31,250 tCO_2 per annum.

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.

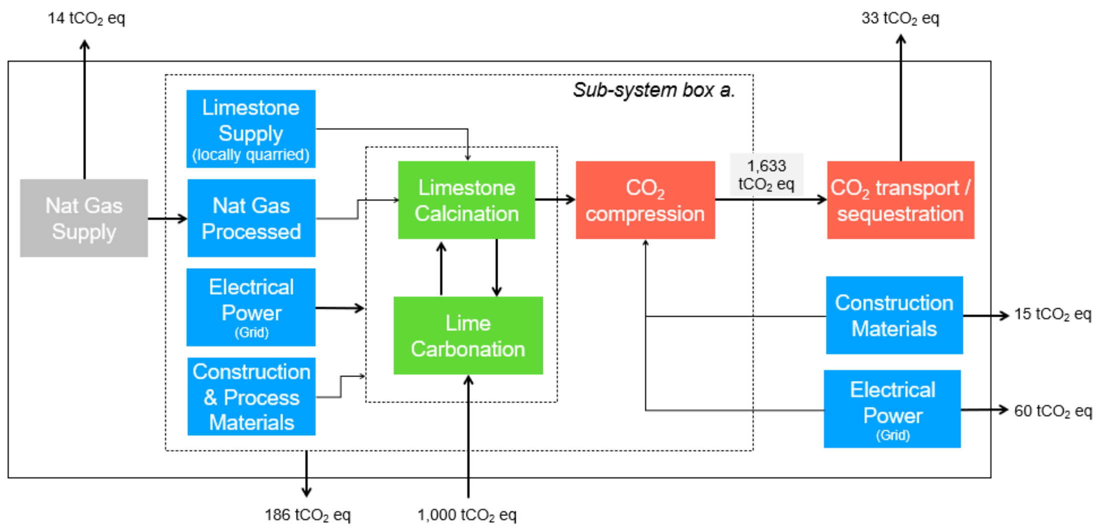
Supporting attachments for section 3: • 2019 FEED Study technical presentation for BEIS (oxy-fuel flash calciner) • Greenhouse Gas Removal Phase 1 Final Report

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	6,250 tCO_2
Gross project emissions	1,925 tCO_2 eq
Emissions / removal ratio	30.8%
Net carbon removal	4,325 tCO_2 eq

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 1,000 tCO_2 eq 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 186 tCO_2 eq will be emitted for every 1,000 t CO_2 eq removed with our air capture modules and 1,633 tCO_2 eq sent for transport and permanent sequestration. In this sub-system, the emissions removal is 18.6% or 81% capture efficiency (see table at bottom of page 4 in attached LCA results). The 186 tCO_2 eq is broken down into 140 tCO_2 eq from electrical power, 15 tCO_2 eq from embedded carbon (LCA of construction and process materials amortized over 20-year asset life), remaining 31 tCO_2 eq from fugitive emissions within calcination and compression processes.

The attached LCA addresses the impact of available grid electricity. To be conservative, we assume the carbon footprint of grid electricity remains at 2018 levels at our proposed site in the UK. Expected improvements in carbon footprint of the available grid reduce the emissions / removal ratio from the above mentioned 18.6% to 12.8% by 2030 and 4.9% if the grid is converted to wind/nuclear.

We expect improvements with scale to our optimal calcination size of a 500 ktpa zero-carbon lime production unit. Using the same 2030 grid electricity assumption as above, the emission to removal ratio improves to 9% (from the comparable 12.8% at smaller scale) and reduces to 3% with wind/nuclear power grid or 4% with solar powered grid (see table on page 5 of attached LCA results).

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 (that will exist e.g., East Coast Cluster, regardless of our project).

Based on a fugitive emission estimate of 2.9% in the UK (Boothroyd et al. 2018) and applying to our 485 tCO_2 eq of natural gas used in calcination (from LCA report), we calculate 14 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). A change to biogas would eliminate fugitive natural gas emissions and create negative Scope 2 emissions (indicative benefits in our attached analysis and of a quantity to be confirmed during refined FEED and LCA conducted in 2024 on the planned 50 ktpa calciner). The attached LCA on ‘sub-system box a.’ addresses carbon dioxide emissions and capture using biogas which yield the same data with respect to the net CO_2 capture results, since nearly all the CO_2 generated by combustion of fuel gas is captured and sequestrated, irrespective of its composition. The energy that is required for the process remains constant whilst the additional inert gasses associated with the biogas only change the mass balance flows, as shown above, and hence the total of sequestered flue gas CO_2.

Despite the potential benefits of biogas in the near/medium term, Origen will additionally progress development/evaluation of alternatives on the technology roadmap including hydrogen and high-grade heat from Triso fuel nuclear small modular reactor (Origen CTO Chris Hankinson was previously Head of Engineering at Rolls Royce nuclear division).

For CO_2 transport/storage, we assume a conservative 2% (our storage partners have indicated potential for <1%) fugitive emissions associated with the 1,633 tCO_2 eq represented by the 33 tCO_2 eq shown in the diagram. These figures are our estimates and will be refined as we work further with the East Coast Cluster and Northern Endurance Partnership infrastructure providers in the UK in addition to conducting third-party verification.

A CO_2 compressor will be built on-site. We conservatively assume the embedded carbon impact is the same as the ‘sub-system box a’, i.e., 15 tCO_2 eq. 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 60 tCO_2 eq reflected in the diagram.

In summary, 308 t CO_2 eq are emitted to remove 1,000 tCO_2 eq resulting in an emissions / removal ratio of 30.8%. We conservatively assume no benefits of scaling from 1,000 to 31,250 tCO_2 eq gross removal system and thus maintain this ratio for our response in the above 4a.

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

This analysis addresses and estimates Scope 1, 2 and 3 emissions for our process to remove carbon dioxide. Pending detailed life-cycle analysis during FEED (to be conducted 2024) for the system scale proposed to Stripe, we do not expect any major components to have been excluded.

Note: the carbon footprint of the limestone source material (e.g., electrical consumption for quarrying and conveying at the Singleton Birch plant) is not included in the above analysis but is expected to be minimal. 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 described in ‘sub-system box a.’ and an additional 2.1 tCO_2 eq in a 1000 tCO_2 gross removal system and thus would have minimal impact on overall emission-to-removal ratio. We will confirm these figures in future detailed, third 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.

> Further to the explanations provided in 4b, the data and assumptions for the life cycle analysis conducted for 'sub-system box a.' can be found in the provided LCA attachment. These are solely modeled and have not yet been independently measured.
>
> 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.

> We will engage an independent expert to verify the LCA during the FEED process to measure/refine estimates from all components within the diagram in 4a and to address unidentified components.

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 will be one DAC plant consisting of 1) one Origen oxy-fuel flash calciner, 2) one tie-in to infrastructure for pure CO_2 to be compressed, transported, and permanently sequestered, 3) to-be-determined quantity of air capture modules based upon 2H22 - 2024 learnings on lime reactivity and module design optimization.
>
> The unit capacity will start at 31,250 t CO_2 gross removal per annum and scale up to near ~400,000 tCO_2 gross removal per unit (~312,500 tCO_2 if carbonation rate remains at conservative 80%), from which we will then modularize / mass produce the unit to pursue giga-scale capacity.
>
> Stripe's procurement of our solution would support the first unit deployment. Any upfront proceeds would help ensure/accelerate the technology development in the period 2H22 – 2024 and/or go toward funding of the first unit's construction in 2025-2027.

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 (25tpa gross CO_2 removal demonstrated)	3,000 tpa calciner pilot operational mid-2022 Carbon removal air capture module designed, to be built by year end 2022
2021	0	N/A	N/A	Commenced construction on 3,000 tpa calciner pilot plant Grant funded passive lime carbonation / CO_2 removal lab work, modeling (GGR Phase 1) Completed lab scale point-source capture carbonation study with Heriot-Watt (see attached reports in shared folder “01 - other related work”)
2020	0	N/A	N/A	Secured 3,000 tpa calciner pilot opportunity with Singleton-Birch Lime-based point-source carbon capture demonstrator commissioned at Heriot-Watt university
2019	0	N/A	N/A	Grant funded FEED study for 50 ktpa calciner completed (see attached presentation in shared folder “00 – primary supporting attachments”)

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.)*

We have estimated deployment costs for our oxy-fuel flash calciner based upon a 2019 grant-funded FEED study for a 50 ktpa calciner. Those costs will refine following incorporation of learnings from the 3,000 tpa pilot plant due to be online mid-2022. Commercial scale calciner deployments will occur within the lime sector in advance of the proposed DAC facility, further refining/reducing costs going into the proposed carbon dioxide removal facility final investment decision by year-end 2024.

The prototype for an air capture module capable of capturing 25 tonnes of CO_2 per year was designed and costed up as the final output from the 2021 BEIS funded project (Greenhouse Gas Removal Phase 1). The cost estimate – based on a combination of quotes for key components and experienced estimates of other components – arrived at an estimate of slightly less than $60k. Accounting for a Lang Factor of 2.5 for construction and commissioning, the cost is $147k for a first-of-a-kind (FOAK). Forward improvements to this cost basis are described in section 6.

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)
0.2	31,250 tCO2/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?

$1,370/ton CO_2

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.

The cost in box 6a includes full capex/opex and associated net removal for our 1) zero-carbon lime calcination system including CO_2 compression (50ktpa lime production scale based on 2019 FEED); 2) CO_2 transport and geologic storage (assumed offtake fee); and 3) air capture modules (at FOAK design cost, highly conservative 80% carbonation rate, unoptimized 25t CO_2 removal per module capacity) integrated to achieve gross removal of 31,250 tCO_2 removal per annum.

In the current model, the blend of capex/opex is ~45/55% with capex amortized over the assumed 20-yr asset life and no capital charge applied.

Electricity costs are assumed to be $125/MWh based upon rates available at our pilot site in the UK (provided by host Singleton Birch). STRIP pricing for natural gas in the UK is used to assume $10.50/mmbtu.

Given the first-of-a-kind, unoptimized state of the air capture module ($147k per module capex installed as mentioned in section 5), this is ~73% of our modeled unit costs.

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.

- With delivery of three key upcoming milestones listed below in question 6f – 6g, we expect costs to decline from current $1,370 to **$450/ tCO_2 by end Q2 2023** through combined higher carbonation rate, lower cost per air capture module and higher capture efficiency (see below for detail).
- Upon completion of this contract with Stripe, we will have incorporated learnings from the 31,250 t CO_2 removal plant into the next scaled up design (5% learning rate ("LR") for calciner and 15% LR for air capture modules) and benefit from scaling factor on the kiln (500 ktpa kiln for a ~313 ktpa gross CO_2 removal system) to a cost of **$324/ t CO_2 by YE 2028**.
- Costs will be **$165/t CO_2 by YE 2030** achieved through optimized siting in N. America (primarily cheaper commodities than UK), a lower-carbon-footprint grid that reduces emission-to-removal ratio to 22.9%, and another iteration of LR improvement from 1-year of operating the first ~313 ktpa CO_2 removal plant
- In the early to mid-2030's, we will go into manufacturing mode with an optimized design realizing economies-of-scale and supply chain efficiencies, further improve emission-to-removal ratio to 11% and complete another two LR cycles with build/operation of a 3.5 M tCO_2 then 35 M tCO_2 scale facility, reaching **$92/ t CO2 by YE 2036**.
- In the second half of the 2030's, we will continue driving down cost while building multiple >100 M tCO_2 facilities to reach giga-scale well below $100/ t CO_2

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)

Initial cost declines are achieved through focused optimization on carbonation of Origen flash calcined lime through the air capture modules. Due to the conservatism in assumptions that underpin current costs, we expect to obtain these reductions with modest improvements in 3 areas: carbonation rates (~80 to 95%), capex of air capture module (from $150k to $60k per module) and air capture module efficiency (25tpa to 100tpa).

Future optimized siting of new plants drives large cost reductions e.g., in N. America with access to cheaper raw materials (than UK) e.g., electricity ($125/Mwh to $70/Mwh), limestone ($10.60 to $4.50/tonne) and natural gas if still used as fuel ($10.50 to $3.00/mmbtu).

Note: the components within Origen's oxy-fuel flash calciner all have high-TRL which is beneficial for deployment risk but with that, we assume a conservative learning rate (LR) of 5% for every doubling of output (or in our deployment, case every 10x scale-up). There is potential de-engineering that has already been identified during construction of the pilot as an example of step-change opportunities that may occur as the pilot comes online. Following pilot and early deployments, we expect a more modest 5% LR. The air capture module technology is more nascent with potential for higher LR's of 10-15%.

In addition to the above, cost realizations will be achieved through improved emission-to-removal ratio to 11% (driven by cleaner electricity grid – significant upside beyond this with fuel-switching) and manufacturing / supply chain efficiencies in 2030s with mass production of the ~313ktpa removal system.

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.

As mentioned in box 1c (Risk 2), the flash calcined lime carbonation mechanism (i.e., through air capture module) still carries significant uncertainty in cost and efficiency. While this will be de-risked over the next 15 months, a less efficient air capture module or lack of gains on capex of each module would limit the potential of our integrated solution to >$500/ tCO$_2$ and require pursuit of alternative methodologies for lime carbonation.

Early deployments will be at sites co-developed with lime producers (e.g., Singleton Birch in UK) minimizing the cost risk of land. Parallel to developments in the UK, Origen is already working on site optimization in N. America and other parts of the world to deliver on assumed energy and commodity price reductions. If we do not achieve above mentioned lower commodity prices, cost will be limited to $170/ tCO$_2$ with other variables constant in our model.

Construction costs overruns pose risks to projects as one-offs but not to the long-term shape of our cost curve.

Learning rates and assumed supply chain efficiencies with mass manufacturing are uncertainties. If not achieved, with half the assumed LR and economies of scale efficiencies, it will be difficult to get below $150/ tCO$_2$ removed with other variables constant in our model.

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 of operations testing program	Demonstrates capability to produce zero-carbon lime - the critical first step to our carbon dioxide removal solution. Establishes baseline plant operating parameters for history matching CFD models and refining commercial scale design / costs. Improves understanding of flash calcined lime characteristics which will be used to refine our air capture module design/efficiency	Construction completed and commissioned by end Q2 2022 Phase 1 operational testing program complete in Q4 2022	Physical visit to the pilot site, photos/videos and reported results of our operational testing.
2	Build FOAK air capture module based on 2021 lab and modeling work at 25 tpa CO_2 removal capacity or greater	Demonstrate baseline effectiveness of air capture module. Enable looping tests with calciner pilot	End of Q4 2022	Physical visit to the pilot site, photos/videos of constructed air capture module.
3	Complete calciner-carbonation looping tests, incorporate operational learnings to expand air capture module capacity to 1,000 tpa CO_2	Further individual air capture module design refinement. Demonstration of multiple air capture modules (up to 40 depending on efficiency) working to remove carbon	End of Q2 2023	Reported findings from looping tests + resulting implications to design for expanded air capture module capacity. Physical visit to

	removal or greater	dioxide as part of a single unit DAC plant. These learnings will be leveraged into the commercial scale DAC plant design for 31,250 tpa CO_2 gross removal (FID by end-2024)		site to see progress.

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 tpa CO_2 removal capacity	0 tpa CO_2 removal capacity due to no sequestration (3,000 tpa demonstrated zero-carbon lime capacity)	N/A
2	0 tpa CO2 removal capacity due to no sequestration (3,000 tpa demonstrated zero-carbon lime capacity)	0 tpa CO_2 removal capacity due to no sequestration (3,000 tpa demonstrated zero-carbon lime capacity, **>25 tpa CO_2 removal capacity with 1 air capture module**)	N/A
3	0 tpa CO2 removal capacity due to no sequestration (3,000 tpa demonstrated zero-carbon lime capacity, >25 tpa CO2 removal capacity with 1 air capture module)	0 tpa CO_2 removal capacity due to no sequestration (3,000 tpa demonstrated zero-carbon lime capacity, **>1,000 tpa CO_2 removal capacity with multiple air capture modules**)	N/A

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	$1,370	$1,370	We do not assume a cost reduction with calciner pilot delivery/testing. However, we have identified potential de-engineering of the calciner design and differentiated carbonation potential of our flash calcined lime which has significant upside to improving cost
2	$1,370	$1,305	Demonstration of 95% carbonation rate (vs previous conservative 80% assumption) with our flash calcined lime in our air capture module. *Note: assume flat 25 tCO_2* p.a. */module until redesign complete in milestone 3.*
3	$1,305	$450	Air capture module capex cost reduced from FOAK $147k/module to $60k/module. Achieve 100t$CO_2$ removed per annum (from 25t CO_2) per module with incorporated design optimization from testing in milestone 1 and 2. Result is less modules required for same removal at lower unit cost.

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 are tackling a global problem that no individual person has authority to resolve. The highest policy impact may be the collective leaders of the world coming together in agreement on mechanisms for carbon pricing and incentives for carbon dioxide removal. In lieu or in

combination of this, we hope to continue to see others follow the lead of corporates and individuals willing to purchase removals to enable technologies such as ours to develop and achieve the scale necessary to be an effective tool to battle climate change.

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

Given the formative stage of our technology development and Stripe's unique insight / external perspective / ecosystem connectedness on carbon dioxide removal, we see a collaborative partnership helping to develop and deliver the best possible version of an Origen carbon dioxide removal solution.

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, private and institutional). Our day-to-day external stakeholders are then local and national trade media, government (BEIS), our direct suppliers (contractors and vendors), 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, we 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.

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 CO2 pipeline, constructing larger calciners, and climate advocacy groups. 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 pre-FEED and 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, using 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?

Original work in this space considered the use of lime for CO_2 removal through enhancing ocean alkalinity. While such an approach is more technically efficient - removing almost double the amount of CO_2 as carbonating 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 will take a proactive project-by-project approach to stakeholder identification and management. In early deployments, Origen will co-develop projects with the lime sector 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 is 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 create high-skilled jobs (in the Humber Region for instance) whilst re-energizing innovation in a region that has seen year on year decline, with industry that is based on clean technology. There is a very strong economic, social, and environmental benefit to our technology and approach.

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. Except for 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, the storage of CO_2 in the UK 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 CO_2 (e.g., within the East Coast Cluster and enabled by the Northern Endurance Partnership).
>
> 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 will occur in the same jurisdiction. International legal regimes might be relevant 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. Indeed, we anticipate that the regulations will actively incentivize CO_2 transport and storage.

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 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*	4,325 metric tonnes CO_2
Delivery window *at what point should Stripe consider your contract complete?*	2027 – 2028
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.*	$1,370 /metric tonne CO_2

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	0.005km^2 (pilot calciner site including single air capture module, 25tCO_2 per module)
2023	0.005km^2 (pilot calciner site including air capture module of 100tCO_2 per stack)
2024	0.006km^2 (pilot calciner site including 10 stacks air capture modules to achieve 1,000 tCO_2 removal)

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)
2022	270m^3 (single unit)
2023	810m^3 (stack of 3 modules)
2024	8100m^3 (10xstack – 1,000 tCO_2 gross removal)

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

1. What sorbent or solvent are you using?

We will be using lime (CaO) and slaked lime $Ca(OH)_2$ during our trials.

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

We expect our zero-carbon lime to be highly reactive with close to 100% carbonation such that 100grams of zero carbon lime results in approximately 78.6grams of CO_2 being removed from the atmosphere. However, for the purpose of sizing the equipment, we have assumed (conservatively) that the zero-carbon lime will only carbonate to ~80% of its full potential capacity such that 100grams zero of lime removes 62.5g CO_2 (as assumed in gross removal calculations of section 3).

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

We will undertake both a looping process using zero carbon lime (CaO) - ($CaO + CO_2 \dashrightarrow CaCO_3 \dashrightarrow CaO + CO_2$ multiple times) and a once-through process ($CaO + CO_2 \dashrightarrow CaCO_3$) to determine which is the optimal approach (the looping process uses less material and less land area, but the once-through process involves less expenditure in handling materials). We will also undertake looping and once-through processes using $Ca(OH)_2$.

Regardless of whether a once-though or looping process is used, each gram of CaO will result in ~0.786g of CO_2 being captured (at 100% carbonation efficiency). We anticipate full release of this CO_2 if the resulting $CaCO_3$ is looped. Some loss of performance (absorption/desorption) is likely during looping, yet to be determined. We also expect hydrating to reduce any impact. These are planned experiments and part of our integrated testing programs in 2023-24.

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)

We will be making zero carbon lime using our oxy-fuel flash calcination technology. Limestone is highly abundant and locally quarried in our project at the Singleton Birch UK host site.

In the longer term, we will continue to partner with the lime industry to co-develop dedicated limestone quarrying, zero carbon lime production, carbon dioxide removal and sequestration facilities.

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

We have the option to make zero carbon lime and allow it to carbonate and then dispose of it. Alternatively, we can loop it. The decision is based on the most economic strategy (to be determined with integrated testing conducted H2 2022 – H1 2023). For looping we can also hydrate which can increase the number of times the zero-carbon lime can be looped. Energy requirements are reflected in the LCA attachment in Section 6.

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)

Our air capture modules used to facilitate zero carbon lime carbonation (and assumed slaker) will be powered by electricity from the local grid. The oxy-fuel flash calciner will use both grid electricity and natural gas (in early deployments) to provide the heat energy required to thermally decompose the $CaCO_3$. We expect a cleaner electricity grid to reduce emission to removal ratio from 30.8% (2018 grid) to 22.9% (2030 grid) to potentially 11% (wind/nuclear power), 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.

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)*

If we use $Ca(OH)_2$ as the primary sorbent, we will need to use water to hydrate the CaO. For every tonne of CO_2 that we capture (assuming 80% carbonation of the $Ca(OH)_2$) we will need about 500kg of water. Water costs vary by location – in the US farmers can pay as little as $5 per 1000$m^3$, whereas desalinated water can be produced at about $1 per m^3.

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

If $Ca(OH)_2$ is used to capture CO2 from the air, then we will need 500kg of water per tonne of CO_2 removed whether it is a once-through process or a looped process. If CaO is used to capture CO_2 from the air, no additional water is required.

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

If we do a once-through process, then we do not cycle the sorbent. If we use a looping process, then the #cycles/day will depend on the characteristics of the lime. At this point we have not produced zero-carbon lime. Tests are planned to investigate looping.

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

Once zero carbon lime has carbonated the CO2 is permanently and stably captured. If looping the material our expectation is there will be a maximum number of times that the zero-carbon lime can be looped, however, at this point in time the number is unknown.

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

For a once-through system the sorbent is replaced every time. For a looping system the material may be looped several times yet to be determined.

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.

Origen's zero carbon lime sorbent will rapidly carbonate to make calcium carbonate. This is a non-hazardous material (calcium carbonate is routinely added to farmland to increase pH and improve agricultural productivity). Additionally, there are markets for finely ground calcium carbonate. Any calcium carbonate that cannot be sold (or up-cycled) would be returned to quarries as landfill which will then eventually be capped and returned to its pre-quarried state. The return of unused or waste limestone material to quarries and capping to return land to its pre-quarried use is standard practice.

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.

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. The technical details of Origen's Direct Air Capture module are being considered for patentability, consequently at the moment it is confidential. With regards to deployment, globally there is an abundance of collocated limestone supplies, natural gas supplies and suitable sequestration sites. This allows Origen to quickly scale up in the near-term to address the GGR challenge. The use of our patented technology and abundant cheap naturally occurring materials has allowed Origen to arrive at a DAC solution that will be advantageous over competitors.

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). Due to the very fine input limestone particle size to our oxy-fuel flash calciner, we have received feedback from the lime industry that use of our technology could expand limestone quarry reserve life by utilizing 'excess' limestone fines that are currently an unusable waste product with existing kiln technology.

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 (most 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.

As mentioned above, it is possible Origen calcination can source 'excess' limestone fines as a feed material which would reduce the amount of milling required. This is an upside benefit that has not been assumed in the LCA work to date.

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 km^2 (active mine at Singleton Birch supporting production of ~0.5 Mtpa lime. Source material required to service our project of 0.05 Mtpa lime will be a fraction of this area.)	Existing Singleton Birch limestone mine
Source material processing	0.005km^2 (50,000 tpa oxy-fueled flash calciner incl. limestone milling and CO_2 gas compressor. 2019 FEED study physical footprint 0.002km2 but only includes equipment)	Vacant land within existing lime processing plant at Singleton Birch (brownfield)
Deployment	Deploying the air capture module at 1,000 tCO2 gross removal to achieve 31,250 tCO2 gross removal (with no further efficiency gains) results in footprint of 0.034 km^2 (includes above source material processing and air capture modules, x-source material mining)	Vacant land within existing lime processing plant at Singleton Birch (brownfield)

5. 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 depth 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 a 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 ~134 MT/yr zero-carbon lime production (assuming ~95% carbonation rate milestone achieved for the produced lime). Our assumed 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., 268 kilns. The associated land footprint of the calcination system is estimated to be 6.16 km^2.	We will locate material processing equipment on vacant land adjacent to source material mining. Not seen as creating competing pressures. Extraction and milling equipment will involve use of steel, but no exotic materials.
Deployment	At an assumed air capture module efficiency of 100tpa CO2 removal, the associated footprint required to remove 100MT CO2 would be 96km^2 (excludes source material mining). This assumes no improvement in removal efficiency from 2024 to the mid-2030s when we would be deploying at this scale. We expect significant opportunity exists to reduce this footprint e.g., if modest improvement to 500tpa gross CO_2 removal per module achieved, land area reduces ~25 km^2.	Exact locations to be determined, but key candidate locations identified in North America, Middle East, and Australia

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

> 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)

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

> We anticipate using lime to remove CO_2 from the atmosphere. The precise extent and rate of the reaction between lime and ambient CO_2 is still the subject of research and will depend on the particular characteristics of the zero-carbon lime that we have yet to produce in our calcination process. What we do know - is that lime does not persist in the mineral record as it rapidly carbonates on exposure to ambient CO_2. We want to know – and will establish – the rate and extent of carbonation of our zero-carbon lime and/or our hydrated zero-carbon lime in ambient air.

8. 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?

> For the air capture modules, we will undertake thermogravimetric analysis to determine the extent of carbonation and isotopic analysis to demonstrate that the CO_2 that is captured by the carbonation reaction originated from the atmosphere rather than from fossil sources. In addition, CO_2 monitoring at air capture module inlet/outlet will provide additional validating measurement of CO_2 removed. These analyses will be performed for optimization/understanding/verification across our deployments (i.e., demonstrate performance in various climates).

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

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

We do not expect environmental release of heavy metals. Limestone deposits (which are plentiful) are used for the production of lime and are routinely screened to ensure there are no heavy metals present in the limestone (as they would affect the usability of the lime being produced). Our flash calcined quicklime and hydrated (slaked lime) will be fine particle size, introducing the potential for a dust hazard. However, these types of products are already routinely handled within the lime sector and at our pilot site by operator Singleton Birch. Pending final optimized design, we expect our process to be mostly within a contained unit, further limiting potential for any environmental releases. Our units will be equipped with standard equipment to monitor, filter and extract any particulate matter to ensure minimal dust emissions.

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

N/A

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

Minimal impact is expected. Our DAC air capture module system is a sealed unit, so (bar faults) it will not impact on organisms. If some lime/calcium carbonate were to be released the effects would be mild. Lime could cause some problems as a caustic material, but those risks would be quickly neutralized by hydration and carbonation in ambient conditions to a mostly benign calcium carbonate. The system will be equipped to monitor for leaks to mitigate impacts of potential material loss of containment events and any associated impacts to organisms.

Depending on areas of deployment, the physical pieces of kit (e.g., our flash calciner) could reduce the amount of sunlight reaching plants at a very local level and hence reduce photosynthesis. At the pilot site in the UK, we will be installing mostly on vacant land within an existing lime processing facility (Singleton Birch).

Impacts to organisms will be studied during the UK pilot period and in conjunction with FEED for this proposed project with Stripe.

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

If negative impacts are detected, we will halt operations immediately until a root cause analysis is performed. If the negative impact cannot be mitigated / remedied, we will abort. Detailed planning for this will be included in standard Design & Operations procedures for our facilities.

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?

Supercritical gas

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?

The proposed project to Stripe will be located at the Singleton Birch Melton Ross site in North Lincolnshire, UK and will use the UK East Coast Cluster CO_2 transport (pipeline) and sequestration infrastructure enabled by the Northern Endurance Partnership (NEP).

Ultra-low permeability sealing cap rock has proven to have the ability to restrict fluid movement for millions of years and four mechanisms of trapping each play a role in preventing any migration to the surface. Durability of the project will be proven during the injection and post injection periods. During the injection period, seismic imaging, pressure monitoring, temperature logging and several other methods will be used to track and monitor the CO_2 within the reservoir. Once the project and injection ceases, the CO_2 plume will continue to be monitored for up to 100 years, ensuring the CO_2 is stationary within the storage reservoir.

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

For future US located plants - Class VI permit

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

50,000 tCO_2 per annum from our project with Stripe as part of larger collective volume in East Coast Cluster infrastructure of up to 27 MM tCO_2 per annum capacity and up to 1 billion tonnes of total CO_2 storage enabled by the Northern Endurance Partnership.

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?

Geologic storage reservoirs are carefully studied to mitigate physical risks of CO_2 leakage, confirmed through 3rd party review prior to use for storage. Uncertainties are mitigated through the utilization of advanced technological methods of reservoir characterization to ensure the properties of the storage reservoir meet technical requirements. The permeance and durability of geological storage will be quantified and confirmed through advanced measurement and monitoring techniques deployed by our experienced/expert sequestration partners e.g., NEP in the UK and Vault 44.01 etc in N. America.

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

The standard techniques for CO_2 sequestration in large saline reservoirs are scalable to accommodate our required injection rates and mitigate uncertainties associated with permanence.