stripe

[Heimdal] Carbon Removal Purchase Application

General Application

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

Company or organization name

Heimdal Inc.

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

Kailua-Kona, Hawai'i, United States

Name of person filling out this application

Marcus Lima

Email address of person filling out this application

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Brief company or organization description

Heimdal removes oceanic CO2 as calcium and magnesium carbonate precipitates

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.

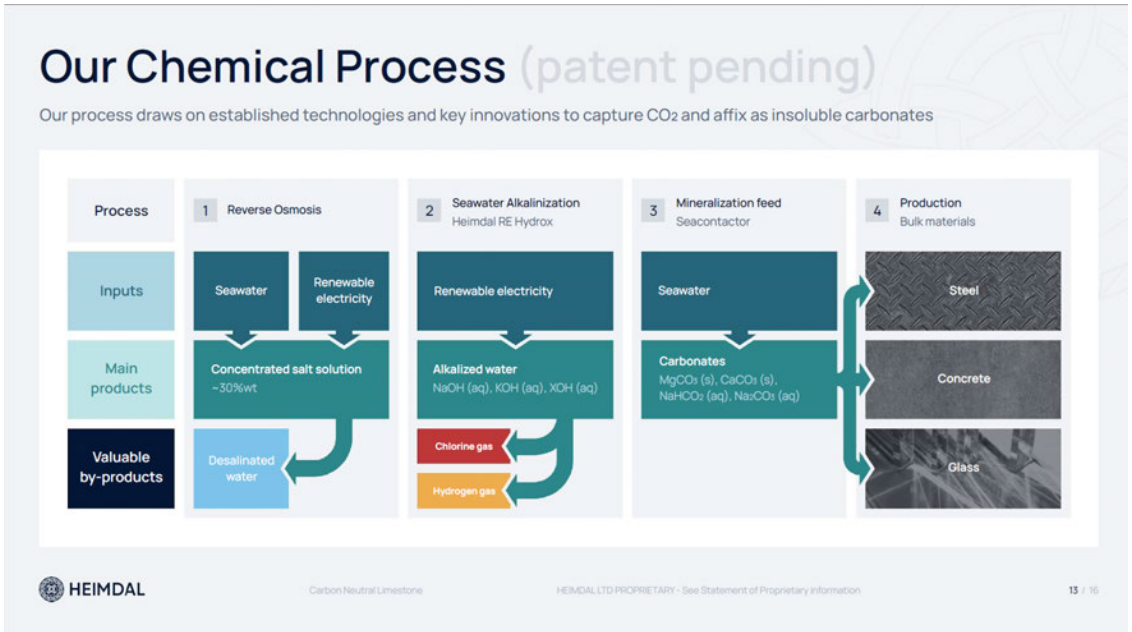
The ocean is the largest natural store of carbon dioxide (CO2) owing to the natural equilibrium of water splitting. This equilibrium can be shifted and accelerated to increase CO2 uptake using cheap renewable electricity. Our solution uses only inexpensive and abundant inputs of seawater and renewable electricity to capture oceanic and atmospheric CO2, increasing oceanic uptake of atmospheric CO2 and chemically storing the trapped CO2 permanently, as a blend of chemically-inert and thermally-stable magnesium and calcium carbonates.

Our solution for atmospheric carbon removal was conceived to prioritize measurability, permanence, and scalability. That is why our process is linear, rather than circular. The upper limit of carbon removal is the size of our raw input: the ocean. Carbon dioxide is assured to be trapped permanently, as the CO2 is *chemically* trapped as insoluble carbonates rather than *physically* stored as CO2, which has the potential to leak as gas from geological storage, giving our solution a higher degree of permanence. Insoluble carbonates have a storage permanence on a geological timescale.

Our carbon capture process begins with seawater concentration using a Multiple Effect Distillation (MED) facility, concurrently generating large amounts of desalinated potable water. The concentrated salt water (between 20%-30% by weight) is then passed through our alkalinization reactor to produce alkalinized water based on the makeup of the local seawater source. Our alkalinized water sorbent is seawater, electrolysed in our proprietary chambers to extract ocean acidity. The extracted acidity (as HCl) can be sold to industrial offtakers. We are exploring possible partnerships with mining companies to treat their mine tailings with our acid.

Alkalinized water is then sprayed through our sea contactor, where it makes contact with dissolved inorganic carbonates (DIC) in seawater. On contact, our alkaline CO2 sorbent shifts the DIC equilibrium from bicarbonate to carbonate. Carbonates of magnesium and calcium are highly insoluble and so crash out as precipitates. Our sea contactor is an open air separate stream of filtered seawater (unconnected to seawater used for making our alkalinized water sorbent) designed to optimize contacting between the DIC in seawater and our sorbent. Due to the strong kinetics of carbonate extraction, open air sea contacting means partial reabsorption of CO2 from the atmosphere occurs whilst further sorbent spraying occurs downstream. This process precipitates a solid mix of mostly calcium and magnesium carbonates along with some hydroxide impurities.

Finally, the solid carbonates are filtered and permanently sequestered underground or used to decarbonize commercial products. These products include glass, concrete, steel, and more. The alkalinized seawater is then re-introduced to the sea through exposure to the atmosphere. This exposure re-gasses the undersaturated seawater to such an extent that an amount of atmospheric CO2 is removed into the seawater equivalent to the amount removed through the carbonate capture, in accordance with Boyle’s Law.



This process also combats the increasing acidification of the oceans from increasing atmospheric CO2, which causes greater oceanic DIC. Reducing oceanic DIC can have a positive environmental benefit on local marine life, especially corals, as ‘closer to normal’ conditions are in effect, as was the case prior to large-scale anthropogenic CO2 emissions.

There are multiple viable solutions for permanent storage of solid carbonates produced by our process. They can be stored permanently in the deep ocean, extracted, and buried; or filtered out and integrated into building products. For example, we are exploring a partnership with Mighty Buildings to integrate our carbonate precipitates into their 3D printing material for permanent storage in the walls of the houses they build, in addition to other building materials companies. These compounds are both thermally- and chemically-stable; requiring >600 C to thermally decompose or interaction with a strong acid to release CO2. This storage mechanism therefore has a durability on a geological timescale of hundreds of thousands, or even millions of years. It would require active human intervention or exceptional planetary events to release CO2 trapped in this form.

Our proprietary solution has solved two important problems for sustainable seawater alkalinization. First, a system is developed that is compatible with intermittent renewable energy sources, including solar and wind farms. We are integrating a hybrid electrical smoothing system of batteries and supercapacitors. This ensures compatibility with the short term fluctuations in power output of directly connected renewable assets (while also providing grid resilience benefits). Second, a key barrier in the electrolysis of impure salts is eliminated. The presence of magnesium and calcium in high concentrations leads to calcination and membrane degradation, which hinders electrolysis. By adding a proprietary mixture of known compounds, we are able to eliminate this barrier, ensuring energy and capital-efficient performance in the long term. This is essential for process economics. This proprietary mixture consists of compounds that are widely and inexpensively available.

In addition to permanent capture of CO2 in carbonates, our process creates useful byproducts, including abundant green hydrogen, hydrochloric acid, and large quantities of desalinated potable water. These byproducts not only help with process economics, but also provide the potential for further industrial decarbonization and socio-environmental benefits. In fact, these products mean that our process is not necessarily reliant on carbon credits for large scale operations. Nevertheless, in these early stages, carbon credit revenue is critical to maturing and downcosting our technology.

The acid product is helpful to process economics in the short term and will help with scaling our solution. However our solution is not reliant on acid revenues at scale. Separating the acidity from the solution also means that the alkalinized sorbent has a net positive carbon sinking effect on the ocean buffer solution. As we scale this process for the long term, the market distortion of acid could present an issue. This technical risk is currently being explored as to what the best method of disposal might be. Possible options include finding a further use for low cost acid, or neutralizing with another widely available waste product. We are in conversations with a global mining company about supplying acid to treat mining tailings, this could be a potentially inexhaustible useful sink for acid we produce.

The possibility of a direct connection to cheap renewable electricity assets, combined with commercialization of adjacent products with large total addressable markets—including desalinated water and green hydrogen—mean a capture cost of ~$100/tCO2 is possible by 2024, assuming a levelized cost of renewable electricity of $50/MWh. As ultra-cheap renewable electricity (~$10/MWh) becomes widely available, capture costs between $20–$50/tCO2 will be possible by 2030. Operational cost of electricity makes up more than 50% of expected lifetime costs of our facilities. As ultra-cheap renewables become widely available, process economics therefore improve dramatically.

Total electrical energy input needed to capture 1 tCO2 is estimated at 2.7 MWh/tCO2. Alkalinization is well understood through comparison with the well-known chlor-alkali process.

We are aiming to deploy a pilot-scale facility (150 tCO2/year capacity) in the next 12 months, and have secured $10M in private venture funding for this deployment. Additionally, we have recently hired an in-house team of talented and experienced engineers to design and build our pilot facility on Hawai'i, in partnership with Terraformation and their existing desalination facility around Kawaihae, Hawai'i County. We will use the concentrated effluent from the desalination facility to make our sorbent and pre-treat the influent in our CO2 removing sea contactor.

Partnering with an existing desalination facility means we are able to deploy much more quickly, as it lowers the barriers of infrastructure buildout and regulatory hurdles. Key barriers to testing out this type of ocean based CDR is gaining the necessary permissions from local, regional, and national authorities. However, desalination facilities already have necessary permissions to extract and discharge seawater. In fact, integrating our solution only has the net positive local effect of increasing pH by a maximum of 0.4 (due to interaction with the ocean buffer). This is likely to have a positive impact on local marine life, including corals in and around the facility on Hawai'i.

Over the proposed project period (Nov. 2021–Dec. 2023) we propose to remove an additional 150 tCO2 for Stripe.

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.)*

Heimdal is the sole supplier of a complete carbon removal solution, from producing the sorbent through to capturing and storing the removed CO_2 as mineral carbonates.

However, to expand the decarbonization potential of our technology, we are developing partnerships for the utilization of our materials. For example, we are exploring the viability of a supplier deal with Mighty Buildings (based in California). Mighty Buildings is an industry leader in 3D printing of houses. We have signed a letter of intent to supply them with carbonates for use as a component in their printing material. They use this printing material to make walls. These works will not release the trapped CO_2.

We are also currently exploring other possible commercial partnerships for utilization of our other products. We have signed letters of intent with global glass and concrete manufacturing companies to decarbonize their processes by using our material including Saint-Gobain, NSG and more. Carbonates are widely used in manufacturing of many bulk materials. It is most obviously used in making cement, by calcining mined limestone. Our calcium carbonates can replace the mined limestone, thereby enabling a net neutral or slightly net negative cement production. Using our carbonates means that the CO_2 emitted in the manufacturing process is already drawn down through our extraction process. We believe this will be a far cheaper method of decarbonizing concrete than other proposed solutions. We also have similar agreements with global glass manufacturers which have a significant need for magnesium and calcium carbonates in their manufacturing process. We will be using some of the carbonates we extract in our pilot facility to test in existing manufacturing plants of our commercial offtake partners.

To be clear, the carbonates in our offer to Stripe will be permanently sequestered by sinking precipitated carbonates into the deep ocean. We are not reliant on any other partner (with the exception of Terraformation) to supply Stripe with the offered carbon removal.

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

1. **Market risk**: There are currently few buyers of carbon dioxide removal (CDR) offsets; fewer still are willing to make purchases from new technologies that have not yet been deployed at scale. Stripe's support in offtaking a portion of the CDR capacity will be a substantial boost in mitigating the market risk for the project, as well as validating the technology for other buyers. We also believe this market will be one that matures over time; however, this capacity needs to be built now as quickly as possible to mature technology and downcost deployment and open up the market for more buyers.

Our process is supported by the ability to secure multiple revenue streams from co-products. In the short term, we are reliant on carbon credit revenue to run a profitable carbon removal facility as our technology matures. In the medium term, before we achieve such scale that we are disrupting the market for hydrochloric acid, but after technology maturity, we can be profitable without carbon credits. At the gigatonne scale, where the purpose of operations is carbon removal *exclusively*, modest revenues from carbon credits are required for profitability. However, for our configuration where the purpose is decarbonizing building materials, a slight green premium for the largest use cases of our products is needed. This is within the current levies being placed on emitters today within emissions trading schemes such as the European ETS ($70/t$CO_2$).

2. **Technical risk**: We currently understand the mechanism of our solution on a small scale (1 tCO_2/yr) and at non-optimized energy efficiency. Successful scale-up of the solution will require work to optimize the sea contacter where alkalinized water and seawater are contacted. We need to better understand the optimal ratio of sorbent addition rate to seawater flow while

ensuring high rates of recovery of carbonate precipitates. The alkalinization reactor will also require work to optimize the concentrated seawater input in terms of softening the feed and degree of concentration. This means pretreating the inlet to remove dissolved hardness (Ca and Mg ions). We have solved the problems of membrane scaling and integration with intermittent power sources, but optimization work remains. The steps needed to improve energy efficiency of alkalinization are well understood in comparison with techniques and practices used in chlor-alkali. Greatest uncertainty is attached to our sea contactor, as our current iteration relied on transporting seawater inland and did not have a continuous inlet of seawater. There is uncertainty around the precise proportional makeup of precipitates beyond that they are carbonates and how this depends on local seawater makeup. Further research needs to be done in optimizing the design and mechanism of our sea contactor to effectively introduce alkalinized water to seawater. 3. **Execution/operation:** No facility of the type we propose exists yet. There is inherent risk in the construction and operation of the facility. Most significantly, it is challenging to accurately predict how labour intensive operating the test facility will be without the data from the pilot facility. Yet, much can be learned from other commercial facilities operating different types of electrolysis to mitigate these risks, as well as from existing desalination plants, which have solved engineering challenges inherent to processing large quantities of seawater. There is also some lingering risk around water access. No legislation exists around processing seawater for the purpose of carbon removal. It is not expressly clear whether there is a right to do so or how complex it might be to gain approval. We are navigating this in the short term by using permissions granted to desalination plants. However, at scale, water access/public goods issues will need to be addressed by government authorities and subsequently us, the suppliers. Aside from the cost of an experienced engineering team, we estimate the likely material cost of building, iterating, testing and optimizing our pilot facility to be \$500k-\$1m. On top of this come the personnel costs in the range of \$1-2m, depending on speed of execution and unforeseen engineering requirements.

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

We have filed for a patent to cover our process and our engineering innovations in the UK. This is not yet publicly available. We are planning to file in the US within the next 3-6 months.

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 2021 - Jun 2022. The end of this duration determines when Stripe will consider renewing our contract with you based on performance.*	November 2021–December 2023
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 2021 - Jun 2022 OR 500 years.*	August 2022–January 2023
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".*	25% delivered in 2022, remaining 75% in 2023. We will keep Stripe appraised of our progress in building our facility. If we achieve our optimistic timeline, a larger delivery in 2022 is possible.
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.*	Millions of years. Solid mineral carbonates are thermally, kinetically, and chemically stable such that storage is on geological timescales.

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

There is ample evidence that calcium and magnesium carbonates remain stable in nature for millions of years, despite fluctuations in atmospheric CO2 concentration. These insoluble carbonates are thermodynamically and kinetically stable over a broad range of conditions, including temperature, pressure, and CO_2 concentrations. Thermal decomposition is possible, but only occurs meaningfully at >600C. Natural conditions, outside of extreme cases, do not decompose mineral carbonates. Importantly, they are stable even when sunk in the ocean. In fact, the deep ocean floor mostly consists of a permanent store of precipitated carbonates.

It is difficult to estimate precise upper and lower bounds given the incredible stability of the carbonates we produce, but we can confidently estimate durability of at least 500,000 years lower bound up to millions of years of effective storage.

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

We have not directly measured the durability of our storage as precipitated insoluble carbonates. However, carbonates are well understood and have been shown to be chemically- and thermally-stable compounds. Our initial storage method is long-term storage at the ocean floor by returning precipitates to the sea from our sea contactor, or alternatively integrating stored carbon into the 3D printing material of Mighty Buildings' 3D printed housing, should testing be successful.

Dissolved inorganic carbonates (DIC) in the ocean are the single largest store of CO_2 on earth. Over time, all anthropogenic carbon emissions would naturally dissolve and be reclaimed by the sea as dissolved carbonates. Ultimately, the stored emissions will remain as carbonate sediments on the ocean floor. Durability of carbonate storage in the ocean is not in doubt. However, we will still perform durability and environmental impact assessments before pursuing this route.

A large amount of academic work has been done to understand the durability of insoluble carbonates, including the following:

- *Feely, R., 2004. Impact of Anthropogenic CO_2 on the $CaCO_3$ System in the Oceans. Science, 305(5682), pp.362-366.*
- *Rau, G., 2008. Electrochemical Splitting of Calcium Carbonate to Increase Solution Alkalinity: Implications for Mitigation of Carbon Dioxide and Ocean Acidity. Environmental Science & Technology, 42(23), pp.8935-8940.*
- *Farmer, J.R., Hönisch, B., Haynes, L.L. et al. Deep Atlantic Ocean carbon storage and the rise of 100,000-year glacial cycles. Nat. Geosci.* ***12,*** *355–360 (2019). https://doi.org/10.1038/s41561-019-0334-6*

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?

<200 words

There are very few durability risks for storage as insoluble carbonates, whether in the sea, underground, or in building products. The main consideration with storage in the oceans is evaluating the environmental impact prior to large-scale deployment. We expect that neither physical nor socioeconomic factors present significant risk due to the geological inertness of carbonates. Yet, studies must be done on how large-scale addition of insoluble carbonates to the sea affects marine life. Current understanding suggests this is unproblematic. There are studies suggesting the effect of increasing ocean alkalinity has a net positive effect on local corals. Nevertheless, experiments must be done to empirically document the lifecycle effect of our atmospheric carbon removal method beyond a theoretical application of Boyle's Law. This will be a priority.

Relevant literature includes:

Albright, R., Caldeira, L., Hosfelt, J., Kwiatkowski, L., Maclaren, J., Mason, B., Nebuchina, Y., Ninokawa, A., Pongratz, J., Ricke, K., Rivlin, T., Schneider, K., Sesboüé, M., Shamberger, K., Silverman, J., Wolfe, K., Zhu, K. and Caldeira, K., 2016. Reversal of ocean acidification enhances net coral reef calcification. Nature, 531(7594), pp.362-365.

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.)*

<200 words

We will be filtering out the precipitated carbonates for our project in Hawai'i. This will allow us to better study their composition and gain a precise understanding of gross carbon removed, as well as supply our commercial partners with some products to test manufacturing their glass and cement in their facilities. We will physically weigh our carbonate products to determine how much CO2 is trapped. The degree of uncertainty will be the proportional makeup of the carbonates. Representative samples will be analyzed periodically by an independent third party lab to determine the proportion of weight attributable to captured CO2 versus metal ions and impurities.

The quantity of carbonates in the product can be accurately measured using x-ray diffraction and mass spectrometry. This will be done at each new location at which the process is deployed to account for the varying composition of the ocean. It will then be done periodically during operations of the process to ensure that there has been no significant alteration in input composition. In between these highly accurate measurement validations, simply measuring the mass of the carbonates in combination with extrapolation of these validations allows for

accurate low-cost carbon accounting.

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	150 tCO2
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	23 kg of H2/tCO2 = 34.5 tCO2

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)*

We will deploy our modular sea electrolysis cells in our pilot facility in numbers sufficient to make enough sorbent to capture 150 tCO2/year as insoluble carbonates. These will be deployed in units of shipping containers. Our capture solvent is not recycled, therefore

production rate determines capacity more than highly uncertain estimates of cyclability. The desalination facility we are working with on Hawai'i has a daily capacity of 300t of seawater. We require 2.7MWh per tonne of CO2 removed (for an efficient system), this will be powered by an off-grid solar array that is currently ~100kW nameplate capacity, operating with a 20% capacity factor. We will be expanding this solar array to 250kW capacity and using a diesel generator in the short term to top up as necessary (likely very little requirement for this before the facility is operational). Available electricity: 250kW*8765hours*20% capacity factor = 438MWh/yr. This is enough capacity for 160tCO2 removal.

As a byproduct of our process, we produce 23 kg of hydrogen/tCO2. Assuming a 60% energy conversion efficiency of H2 to electricity, this replaces 600 kWh of natural gas from combined cycle gas turbines (CCGT) for electricity generation with emissions of 380kgCO2/MWh, though this can vary by CCGT. This is equivalent to 0.23 tonnes of CO2 emissions avoided per tonne captured. 0.23tCO2 avoided/tCO2 removed * 150tCO2 removed = 34.5 tCO2 avoided.

If used in building materials, our solution avoids even more emissions. However, since the Stripe offer will not involve building materials, we have not included that calculation.

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

1 metric tonne CO2/yr

d. We are curious about the foundational assumptions or models you use to make projections about your solution's capacity. Please explain how you make these estimates, and whether you have ground-truthed your methods with direct measurement of a real system (e.g. a proof of concept experiment, pilot project, prior deployment, etc.). We welcome citations, numbers, and links to real data! *(E.g. We assume our sorbent has X absorption rate and Y desorption rate. This aligns with [Sorbent_Paper_Citation]. Our pilot plant performance over [Time_Range] confirmed this assumption achieving Z tCO_2 capture with T tons of sorbent.)*

Our current demonstration facility in Carterton, UK, has directly measured performance of 990 kg of alkalinized water CO2 sorbent needed per tonne of CO2 sequestered. Sorbent production is the key metric for system capacity and energy consumption. Carbon removal efficiency of the sorbent is high, with 99.5% of alkalinized water leading to removal of DIC as insoluble Mg and Ca carbonates. Carbonate recovered against alkali added has been measured to 2.1:1 in our Carterton facility (2.1g of carbonates per g of alkalinized water sorbent sprayed).

Work needs to be done on gathering data from experiments showing CO2 drawdown from the atmosphere to verify our expectations that carbonate precipitation leads to equivalent CO2 drawdown from the atmosphere into seawater as Boyle's Law suggests.

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

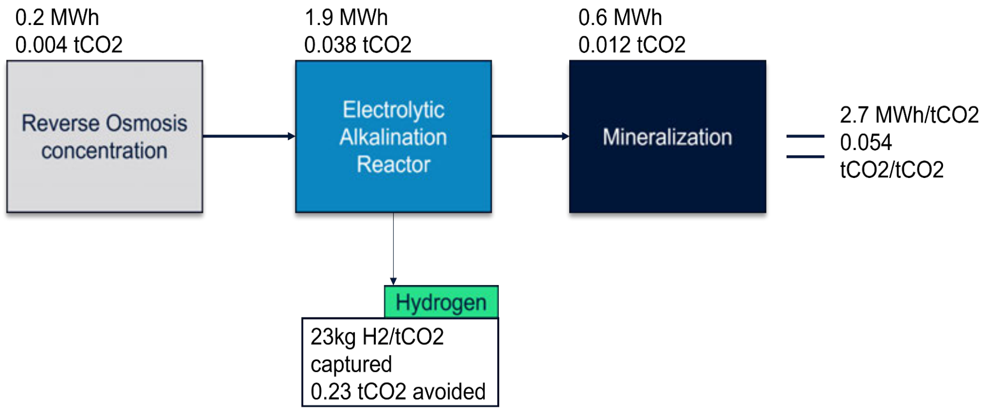
> We have been a team of two building this technology since the beginning of 2021, so we do not currently have any data that is available via an online link. However, we would be happy to provide Stripe with our existing raw data upon request.
>
> Since we raised $10m in private funding in September 2021, we are now a well-funded team of eight deeply experienced engineers and operators building a full pilot-scale facility in the next 6-12 months that will rival most existing pure-DAC facilities in scale. Going forward, using our additional resources and perfect pilot project conditions in Hawai'i; gathering more data, doing full independent life cycle analyses, and environmental impact assessments is a priority. We will provide this (and other reports) to Stripe as we complete them, as part of our offer/contract.

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	150 tCO2
Gross project emissions	8.1 tCO2
Emissions / removal ratio	0.054
Net carbon removal	141.9 tCO2

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



Sources: Wind turbine lifecycle emissions are estimated at 20gCO2/kWh at the upper end Bhandari, R., Kumar, B. and Mayer, F., 2020. Life cycle greenhouse gas emission from wind farms in reference to turbine sizes and capacity factors. *Journal of Cleaner Production*, 277, p.123385.

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 diagram above includes all elements of the system, apart from minimal internal hydraulics for handling fluids in the system. The internal hydraulics account for 1% of energy requirements. The only system inputs are seawater and renewable electricity to drive alkalinization, seawater concentration, and pump seawater needed for mineralization in the sea contactor.

What is not included is transportation of precipitated carbonates to a storage site other than the ocean. For large-scale deployment, the site of storage/usage (whether in building products or in the ocean) will be close to the project site.

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.

<200 words

The energy balance listed above is based on real-world data for state-of-the-art operations of comparable processes. Reverse osmosis is well understood to operate at 2 kWh/m^3 of recovered pure water. The key electrolytic alkalinization reactor operating efficiency is based on the need to produce the equivalent hydroxide amount, 908 kg NaOH, under membrane chlor-alkali (2.3 MWh/ECU). This is the level of efficiency we expect to reach for our alkalinization reactor. For the mineralization step, existing real world pumps are used to derive energy, processing ~11,000 tonnes of seawater per tonne of mineralized CO_2. This equates to ~600 kWh/tCO_2 at a likely head height of 8 metres, using commercially-available pumps operating at 400 W with a capacity of 120 L/min.

- European Commission Joint Research Centre, 2014. *Best Available Techniques (BAT) Reference Documents for the Production of Chlor-alkali*. Luxembourg: Luxembourg Publication Office of the European Union.
- O'Brien, T., Bommaraju, T. and Hine, F., 2005. *Handbook of Chlor-Alkali Technology*. New York: Springer.
- Shrivastava, A. and Stevens, D., 2018. Energy Efficiency of Reverse Osmosis. *Sustainable Desalination Handbook*, pp.25-54.
- Li, S., Duran, K., Delagah, S., Mouawad, J., Jia, X. and Sharbatmaleki, M., 2020. Energy efficiency of staged reverse osmosis (RO) and closed-circuit reverse osmosis (CCRO) desalination: a model-based comparison. *Water Supply*, 20(8), pp.3096-3106.

e. If you can't provide sufficient detail above in 4(d), please point us to a third-party independent verification, or tell us what an independent verifier would measure about your process to validate the numbers you've provided. (We may request such an audit be performed.)

<100 words

The most uncertain number is the precise energy input needed for the alkalinization and mineralization in the sea contactor. Conditions are sufficiently similar to membrane chlor-alkali that this is a reliable baseline (+/-10%).

Carbonate precipitation from seawater by the addition of alkalinity is not well studied. However there are studies that suggest very carbonate precipitation of seawater is highly efficient where 99.5% of added alkalinity precipitates mineralized carbonates of magnesium and calcium. These precipitation efficiencies were also observed in our lab when testing seawater collected in Southampton that was used as the feedwater to our demo scale system in Carterton.

Albright, R., Caldeira, L., Hosfelt, J., Kwiatkowski, L., Maclaren, J., Mason, B., Nebuchina, Y., Ninokawa, A., Pongratz, J., Ricke, K., Rivlin, T., Schneider, K., Sesboüé, M., Shamberger, K., Silverman, J., Wolfe, K., Zhu, K. and Caldeira, K., 2016. Reversal of ocean acidification enhances net coral reef calcification. *Nature*, 531(7594), pp.362-365.

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

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

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

The unit of deployment for this project will be one pilot plant at 150 tCO_2/year of carbon removal. The plant will be integrated with Terraformation's existing desalination facility in Hawai'i. This system will have 4 shipping-container-sized modules at just under 40t/year capacity each.

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

Year	Units deployed (#)	Unit cost ($/unit)	Unit gross capacity (tCO_2/unit)	Notes
2021	1	$10,000	1 tCO_2/year	Unit cost includes cost of materials only. Purchased off the shelf from mainstream suppliers including RS Components (UK), Amazon (UK), some speciality suppliers, and local suppliers of custom metal components.
2020	1	~$1,000	50 $kgCO_2$/year	Original proof of concept system
2019				*<50 words*
...				

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

The proof of concept system was built on a limited budget using less-than-ideal materials and design choices. Costs decreased with the production of the demonstration-scale system, as material inefficiencies and design choices were improved. However, inefficiencies remain due to relatively small scale and costs are expected to improve.

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	150 tCO2/unit

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

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

a. What is your cost per ton CO_2 today?

Our cost today is ~$1,200/tCO2 for our demo-scale system with a capacity of 1 tCO2/year . Carbon removal using the next generation pilot-scale system offered to Stripe will operate at a significantly lower cost of $250 per tonne CO2 removed.

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, assumptions around energy costs, etc.

<100 words

Deployment and operating costs are included, as is 50% of expected additional cost of developing a scalable low-cost modular engineered pilot system. The Hawai'i site uses off-grid solar (built in 2019) as the main source of electricity with levelized cost of electricity of ~$40/MWh.

Learnings from the larger pilot system will significantly de-risk uncertainties around energy balance and bringing removal cost well below $100/t for our first commercial scale iteration. The current demo-scale cost includes OPEX as well as CAPEX, assuming a running lifetime of 10 years and energy costs of $180/MWh.

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

Milestone #	Milestone description	Why is this milestone important to your ability to scale? (200 words)	Target for achievement (eg Q4 2021)	How could we verify that you've achieved this milestone?
1	Performance optimization of demo-scale alkalinization and mineralization	Experimentally determining comprehensive configuration optimization data is essential to ensuring successful scale-up. Configuring alkalinized water mixing rate, rate, and efficiency of sorbent production, and optimizing precipitate recovery mechanism. This is important to the ability to scale, as every kWh reduced per unit of carbon dioxide captured dramatically decreases the cost per tonne of CO2 captured. These further optimisations will not only lead to increased energy efficiency of the system, but also a better understanding	Q4 2021	We will compile a report including technical performance data and publish a peer-reviewed paper based on our findings outlining the system details in the course of 2022.

		of reaction rates, which will enable better sizing of the pilot plant and other future plants. *<200 words*		
2	Pilot facility design *<100 words*	Establishing pilot facility system components, dimensions, and planned layout/design. This will deliver a complete understanding and detailed schematic of the systems required to automate the system. This will enable the rapid development of the plant and ensure that all of the engineers are on board with a uniform design and so technicians are able to execute with no uncertainty. This will also form the basis for the design of future plants through the modularisation into shipping containers. This will enable future plants to be developed and optimized upon an existing plant and with the dimensional constraints of the modules established. *<200 words*	Q1 2022	We will show you our detailed pilot facility system plans and contracts for leasing land and any EPC contracts deemed necessary. We will also share pictures/data from component testing. We are building a modularized system so we can also provide demonstrations of prototype modules. *<100 words*
3	*Pilot system fabrication,*	Construction and initial operation of pilot facility. Begin	H2 2022	We will invite you to come visit our

	commissioning, and initial operations	delivering on carbon removal contract and other commercial contracts. This stage will help gather invaluable live operational, technical, and economic data for the next commercial scale facility. The primary operational data that will be gathered is the energy use per tonne of carbon dioxide captured. As this plant will be directly powered through an onsite solar array, data on how the system can be integrated directly with an intermittent renewable asset will also be gathered. This is vital not just for the low-carbon impact associated with renewable intermittent assets, but also as solar and wind are proving to be significantly more cost-effective than other energy sources. Fabrication will also inevitably lead to significant improvements in the design of the system and its efficiency. These improvements will then be carried through to the commercial scale plant and improve the economics. A better understanding of the process economics also enables better		facility and show you our physical extracted CO2. We will also have a wide range of performance data and reports that we can provide digitally.

		gearing for use in debt financing structuring of future plants. *<200 words*		

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

Milestone #	Anticipated total gross capacity prior to achieving milestone (ranges are acceptable)	Anticipated total gross capacity after achieving milestone (ranges are acceptable)	If those numbers are different, why? (100 words)
1	1 tCO2/yr	1 tCO2/yr	
2	1 tCO2/yr	1 tCO2/yr	
3	1 tCO2/yr	150tCO2/yr	Pilot facility on Hawai'i becomes operational

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

Milestone #	Anticipated cost/ton prior to achieving milestone (ranges are acceptable)	Anticipated cost/ton after achieving milestone (ranges are acceptable)	If those numbers are different, why? (100 words)
1	$1,200/tCO2	$1,200/tCO2	This is the operational cost of our demonstration system.
2	$1,200/tCO2	$1,200/tCO2	
3	$1,200/tCO2	$250/tCO2	Once our pilot facility comes online, our costs will be reduced drastically per tonne as we capitalize on system optimizations realized in milestone 1 and integrated in milestone 2.

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

> We need a lot of upfront capital to build and deploy our units at scale. This can be done with debt financing; however we need to cross over to the point where investing in building one of our facilities is a low risk investment akin to solar and wind power. We would ask rich philanthropists (Bill Gates!) to direct their capital towards deployment of this technology.

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

> Introductions in academic communities to trusted third parties that can help us verify our approach. Encourage other large corporations and governments to take similar action to Stripe on carbon removal, as a matter of corporate policy. We need a large and thriving global market for carbon removal, and for consumers to expect this. Stripe is a pioneer, but we hope you will become one amongst many climate champions. As Mark Carney said, we need a high quality voluntary carbon offset market worth >$100bn a year.

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

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

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

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

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

<100 words

> Key stakeholders include local governments and residents near our future coastal facilities. We will engage with local governments to ensure our operations do not negatively impact their local marine and terrestrial ecosystems as well as their livelihood activities. Given the benign nature of our activities and the positive environmental impact, we do not anticipate serious reservations from these entities, but we will engage with stakeholders in parallel with the development process. We will run a public outreach process similar to that run by wind and solar farm developers to ensure continued support and engagement from the local community.

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

<100 words

We have a strong relationship with Terraformation out in Hawai'i, the owners and operators of the existing desalination plant we will be integrating into our system. They have strong connections to the local authorities and community and will be making introductions as we set up in the State. They will also help us engage with the local community. We prioritize being good stewards of the land and community around us.

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?

We have learned about the deep importance placed on responsible land stewardship in Hawai'i. The land is uniquely and deeply tied to the indigenous culture in the State. If we can be good stewards of the land as we build out our solution in Hawai'i, where such deep importance is placed on this, then we will have set a gold standard for managing local concerns/issues around implementing our solution in sensitive ecosystems.

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

From this learning, we have increased the extent of planned stakeholder outreach and potentially environmental impact assessment. As we scale up, our engagement needs to become more efficient but tailored to larger deployments and to the local communities. More land/people and local authorities will be involved. We will need to handle stakeholder management across multiple jurisdictions with different requirements, and local conditions and expectations. Building a facility in Hawai'i with the cultural and environmental context here will be different to coastal UK. We will carry over the strictest stakeholder management, even where not legally required or expected, and tailor this to local contexts.

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

There are potential social and health impacts, in addition to the economic benefit that comes from materials being shipped and supplied from our facilities. We will address these as far as possible by siting our facilities near or adjacent to the main offtakers of products we produce and sell to external parties. This will minimize disruption and transportation emissions.

Potential impact on siting of facilities on indigenous lands or in disadvantaged communities. Engage with local community groups and governments to make sure that siting does not impact indigenous ways of life or disproportionately affect underrepresented groups.

11. Legal and Regulatory Compliance (Criteria #7)

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

<100 words

We have explored the regulatory framework in Europe and there are no specific approvals required to treat seawater ,as we do not meaningfully impact the discharged seawater (only CO_2 reduced). However, planning permission from local authorities to implement, build and operate a facility like ours is needed.

The chief challenge we face is in gaining local approval for building coastal facilities. Depending on the jurisdiction, building in coastal zones is especially hard. We are navigating this in the short term by partnering and co-locating with facilities with existing approvals such as the pilot project on Hawai'i.

b. What permits or other forms of formal permission do you require, if any? Please clearly differentiate between what you have already obtained, what you are currently in the process of obtaining, and what you know you'll need to obtain in the future but have not yet begun the process to do so.

Permits that may be required are highly dependent on the jurisdiction of the site. We need to be in the correct zoning and will need at least building, plumbing, and electrical permits. In the US we may have to comply with NEPA or equivalent state laws around environmental impact assessments.

However, for the short term we get around these requirements by building in non-permanent (containerized) structures around a desalination facility with all the necessary approvals pre-existing.

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

There is not much of a regulatory framework to cover what we do. Most regulation around using seawater is for facilities that have a negative impact on water quality or marine life. However, our solution has no impact on water quality and a positive local and global impact on marine life (by combating ocean acidification), so regulation should be more straightforward. This will need to be further assessed as we expand the number and sizes of our sites.

d. Does the project from which you are offering carbon removal receive credits from any government compliance programs? If so, which one(s)? (50 words)

No

12. Offer to Stripe

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

	Offer to Stripe
Net carbon removal (metric tonnes CO_2)	141.9 tCO2
Delivery window (at what point should Stripe consider your contract complete?)	December 2023
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.*	$250/tCO2

Application Supplement: Ocean

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

Physical Footprint (Criteria #1)

1. Describe the geography of your deployment, its relationship to coastlines, shipping channels, other human or animal activity, etc.

<200 words

Our deployment will be on the island of Hawai'i co-located with a Terraformation desalination plant and a 100kW solar array. The site is near Kawaihae on the north end of Big Island, Hawai'i. The site is off-grid, but has access to diesel back-up power if necessary. The desal facility draws seawater from a drilled well that is a mixture of brackish and seawater. We can drill additional wells to expand capacity if needed.

In general, our solution needs to be deployed on or near coastlines anywhere in the world to minimize the cost of moving and processing seawater. For economic and energy efficiency, plants also need to be built in near proximity to cheap renewable electricity assets, or where there is free land that can be developed for this purpose. The need for concentrated seawater means integration with existing desalination plants is ideal.

Because our solution is completely non-hazardous, it can be safely deployed next to human population centres. There are some early studies suggesting that alkalinity enhancement is beneficial to local coral reefs. We can consider locating plants close to vulnerable coral reefs.

2. Please describe your physical footprint in detail. Consider surface area, depth, expected interaction with ocean currents and upwelling/downwelling processes, etc.

   a. If you've also filled out the Biomass supplement and fully articulated these details there, simply write N/A.

   <200 words

Our plants are not directly oceanic, but are located on or close to the shoreline. We extract two streams of seawater filtered of organic material. The first stream is treated in our alkalinization reactor separate from the seawater source, minimizing any incursion in the ocean. Our second—much larger—stream is fed into the sea contactor to make contact with our alkalinized water to initiate precipitation. Our actual oceanic interface is limited to the inlet and outlet of seawater as our facilities are coastal.

Our outlet is benign CO_2 reduced, alkalinity enhanced seawater (<0.4pH greater than seawater). By integrating our solution with desalination facilities, we in fact eliminate the negative local externalities of discharging highly concentrated saline water. This means there is a much improved case for accessing potable water through a desalination solution that also captures atmospheric CO2.

The physical footprint of our Hawai'i pilot facility on land is estimated to be 600-1200sqft.

3. Imagine, hypothetically, that you've scaled up and are sequestering 100Mt of CO_2/yr. Please project your footprint at that scale, considering the same attributes you did above (we recognize this has significant uncertainty, feel free to provide ranges and a brief description).

    a. If you've also filled out the Biomass supplement and fully articulated these details there, simply write N/A.

    <200 words

Oceanic footprint is not applicable as our facilities will be based on land. At a scale of 100 MtCO2/year, we will be processing 100 billion tonnes of seawater per year and generating ~200 Mt of insoluble carbonates. The main footprint will be the land area needed to build the renewable energy required to power this facility with renewable electricity. At our expected energy efficiency of 2.7 MWh/tCO2, removing 100 MtCO2/yr will require 270 TWh/yr; approximately equivalent to the annual energy demand of the UK. Both solar farms and/or wind turbines can power our solution. Assuming wind turbines, they have a permanent land footprint of 0.3 hectare/MW, assuming a capacity factor of 40% means a total land footprint of 23,100 Ha when operating our solution at 100 MtCO2/year.

The relative physical footprint of non-electricity generating equipment is minor at 0.6m2 per tonne of CO2/year capacity. Equivalent to 6000 Ha at 100MtCO2/year scale.

Denholm, P., Hand, M., Jackson, M. and Ong, S., 2009. Land-Use Requirements of Modern Wind Power Plants in the United States. [online] National Renewable Energy Laboratory. Available at: <https://www.nrel.gov/docs/fy09osti/45834.pdf>

Potential to Scale (Criteria #2 and #3)

4. Building large systems on or in the ocean is hard. What are your core engineering challenges and constraints? Is there any historical precedent for the work you propose?

<200 words

Our system draws on the ocean but is not built in the ocean. Engineering challenges specific to this are therefore limited. Extracting, filtering, and concentrating large amounts of seawater without disturbing coastal marine life will be the main challenge.

However, there are significant existing facilities that do this and have developed technical solutions to these challenges. The best comparison in terms of engineering challenges is desalination plants. They have an enduring history of overcoming barriers to successful near-ocean engineering operations specifically regarding the near-ocean treatment of seawater, managing the local effects of drawing and discharging large quantities of water.

For co-located plants, there will be near zero additional impact on the ocean, other than increasing local CO2 uptake.

Externalities and Ecosystem Impacts (Criteria #7)

5. How will you quantify and monitor the impact of your solution on ocean ecosystems, specifically with respect to eutrophication and alkalinity/pH, and, if applicable, ocean turbidity?

Our solution relies on the introduction of alkalinity to remove DIC from the ocean, resulting in a local net increase in alkalinity and decrease in dissolved CO2 such that atmospheric CO2 will dissolve to reform DIC, consequently restoring the ocean/atmospheric CO2 equilibrium.

Some of the carbonates we remove from the ocean—in particular the calcium carbonates—have useful economic applications that justify removal, such as for use in building materials including concrete, gypsum, and glass. Even if used in making these building materials through a process that releases CO2, there could still be net carbon removal from materials like concrete re-absorption of a proportion of the emitted CO2 during the setting process.

However, if carbonates are not extracted to be buried underground or used in building materials, they can easily be disposed of by sinking them in the ocean, which we would do well offshore and away from any sensitive wildlife and ecosystems. Nevertheless, we need to evaluate the wider effect of doing this at scale before deploying this option. The ocean is a large, complex system, therefore understanding the precise effect of sequestering insoluble carbonates in the ocean must be established first. However, chemical carbonates are considered benign and are chemically inert and should not interact with the ocean to a significant extent, with the possible exception of providing material access for coral growth and crustacean proliferation. If deploying this solution, we would strictly monitor local conditions, which—if any—are likely to be the most affected. Monitoring global effects is more challenging without deploying the solution at scale; but modeling—using our current understanding of the oceans—could provide the confidence needed.