[Skyology]

Carbon Dioxide Removal Prepurchase Application

Summer 2023

General Application

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

Public section

The content in this section (answers to questions 1(a) - (d)) will be made public on the Frontier GitHub repository after the conclusion of the 2023 summer purchase cycle. Include as much detail as possible but omit sensitive proprietary information.

Company or organization name

Skyology

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

San Francisco, CA

Name(s) of primary point(s) of contact for this application

Swiss Williamson

Brief company or organization description <20 words

Skyology integrates ocean alkalinity enhancement (OAE) into existing wastewater treatment plants (WWTPs) to capture and store carbon dioxide.

1. Public summary of proposed project[1] to Frontier

a. **Description of the CDR approach:** Describe how the proposed technology removes CO_2 from the atmosphere, including how the carbon is stored for > 1,000 years. Tell us why your system is best-in-class, and how you're differentiated from any other organization working on a similar approach. If your project addresses any of the priority innovation areas identified in the RFP, tell us how. Please include figures and system schematics and be specific, but concise. Aim for 1000-1500 words.

Technology Summary. Skyology integrates ocean alkalinity enhancement (OAE) into coastal wastewater treatment plants (cWWTPs). Our low-build process accelerates traditional OAE cycle time by controlling the drivers of air-water gas exchange. Our approach combines the virtually unlimited carbon storage of the ocean with the scale of global water treatment infrastructure. See Figure 1. As a result, Skyology uses human waste streams to remove atmospheric CO_2 and safely store it in the ocean as bicarbonate. The co-benefit is the deacidification of local ocean habitats disproportionately impacted by Ocean Acidification (OA) problems.

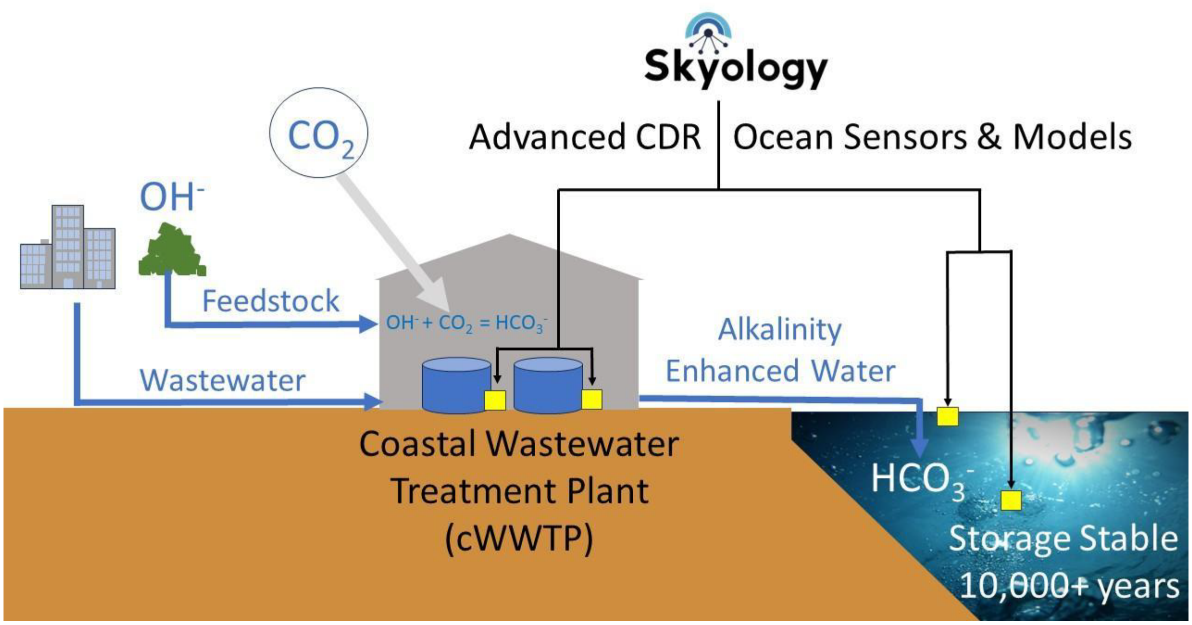

Figure 1. Skyology system technology summary.

Ocean Acidification. The anthropogenic carbon dioxide (CO_2) emissions are elevating the atmospheric CO_2 parts per million. The ocean and atmosphere equilibrate, forcing the ocean to absorb CO_2. The CO_2 reacts to form carbonic acid (H_2CO_3), increasing the ocean's acidity. Consequently, the ocean is now 25% more acidic than 200 years ago. The acidic pH damages keystone species, including corals, shellfish, and coccolithophores. The acidic pH is corrosive to carbonate minerals in the ocean, and these organisms' bodies decay and seemingly "melt" if the water becomes too acidic. The process is similar to

[1] We use "project" throughout this template, but note that term is not intended to denote a single facility. The "project" being proposed to Frontier could include multiple facilities/locations or potentially all the CDR activities of your company.

osteoporosis in human skeletons, except these organisms' skeletons are on the outside. The earth has lost 50% of its coral reefs in the last 30 years and is on track to lose the remaining reefs in the next 30 years without intervention. (Tyler, et al., 2021) The loss of 30% of all marine species will be catastrophic to the marine ecosystem. There is an urgent need growing for active mitigation of ocean acidification.

Ocean Alkalinity Enhancement. How can we store carbon in the ocean where Earth wants to place it without damaging marine ecosystems? The ocean is the largest CO_2 reservoir in the world. Our ocean holds around 38,000 gigatons (Gt) of carbon (Bosch et al., 2010). That is 16 times as much carbon as the terrestrial biosphere, which includes all plants and the underlying soils on our planet, and around 60 times as much as the pre-industrial atmosphere. The global oceans have a net uptake rate of 0.60 to 1.34 Gt of carbon each year (Takahashi et al., 1997). Ocean Alkalinity Enhancement (OAE) aims to speed up the ocean's capture and storage of excess atmospheric CO_2 through a product of alkalinity instead of acidification. OAE accomplishes this goal by accelerating the earth's non-organic carbonate cycle in three steps, as shown in Figure 2.

Step 1 is mineral dissolution, in which an alkaline mineral dissolves into seawater. This gives rise to a cation and alkalinity in the form of hydroxide (OH^-).

Moving to Step 2, we have a shift in carbonate equilibrium, where OH^- reacts with inorganic carbon to convert aqueous CO_2 (CO_2(aq)) into bicarbonate (HCO_3^-), which can subsequently combine with OH^- to form carbonate (CO_3^{2-}). This has the effect of depleting CO_2(aq) in the seawater.

And here is where things get really interesting - Step 3 replenishes carbon dioxide by transferring gaseous CO_2(g) from the atmosphere into seawater. By combining these three steps together, OAE turns the ocean into "a sponge" for CO_2.

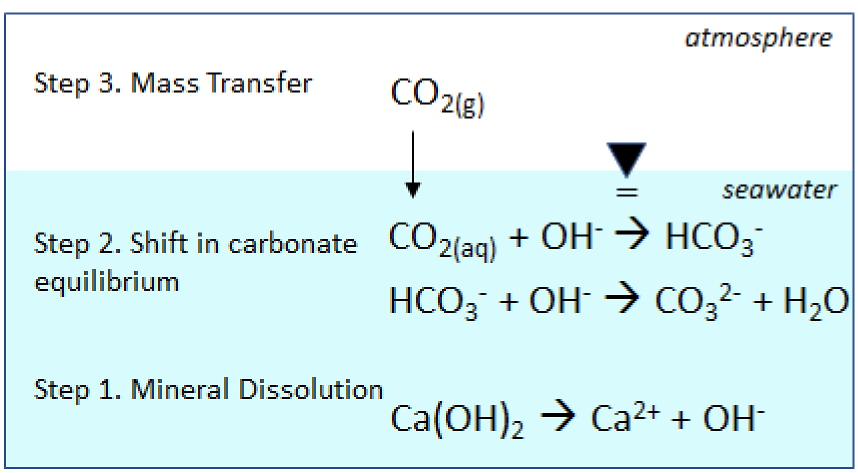

Figure 2. An illustration of three key steps in Ocean Alkalinity Enhancement (OAE)

The actual amount of carbon that the ocean can absorb can be estimated by considering two properties of seawater: Total Alkalinity (TA) and Dissolved inorganic carbon (DIC).

DIC measures the actual amount of inorganic carbon that the seawater holds. Since the concentration of CO_2(aq) in seawater is small, DIC is approximately the sum of the

DIC measures the actual amount of inorganic carbon that the seawater holds. Since the concentration of CO_2(aq) in seawater is small, DIC is approximately the sum of the concentrations of all other carbonate species, namely bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}):

$$DIC = [HCO_3^-] + [CO_3^{2-}]$$

Alkalinity, on the other hand, defines the ability of water to neutralize acid. And because the ocean is primarily a carbonate-buffered system, the total alkalinity (TA) can be written as the sum of the concentrations of bicarbonate and twice the concentration of carbonate, as each mole of CO_3^{2-} can neutralize two moles of acid.

$$TA = [HCO_3^-] + 2\,[CO_3^{2-}]$$

When we combine these two equations, we arrive at the equation

$$DIC = TA - [CO_3^{2-}]$$

This equation shows while DIC increases in proportion to TA, its benefit is reduced due to the formation of CO_3^{2-}. In the literature, this is described as the non-linear relationship of the carbonate system (Moras et al., 2022).

In practice, a fraction of DIC converts to CO_3^{2-} and this reduces the efficiency of TA to remove CO_2 by about 20%. Therefore, each mole of alkalinity generated through mineral dissolution results in the sequestration of 0.8 moles of CO_2 from the atmosphere.

Skyology's Advantages in OAE.

1. **Speed of Deployment -** Skyology eliminates the need for large capital expenditures like floating platforms, holding tanks, coastal plant construction, and outfall permits. The advantage is devised by using specific components within the existing WWTP system to implement OAE, rather than build from scratch. By reducing the engineering overhead means Skyology project sites are low-risk for our pilot partners to try. Curtailing risks and switching costs for our partners means not only swifter adoption but a clear path to becoming a climate-relevant CDR supplier.

2. **Speed of Delivery -** Along with traditional ambient capture associated with OAE, Skyology captures point source CO_2 before it is released into the atmosphere. The Skyology system takes advantage of the influent CO_2 sources. Capturing concentrated CO_2 can happen in a matter of hours instead of the years modeled in

ambient atmosphere OAE capture (Köhler et al., 2013). For our customers, this means faster credit delivery time for our customers.

3. **Measurement** - Using large contained mineral OAE reactors helps our system bridge the gap between the precise measurability of electrochemical OAE and the cost-effectiveness of open-system coastal enhanced weathering. Containing mineral reactions helps Skyology measure influent, effluent, and the delta between. More precise measurement means we can provide a greater level of certainty for our purchasers. See Figure 3.

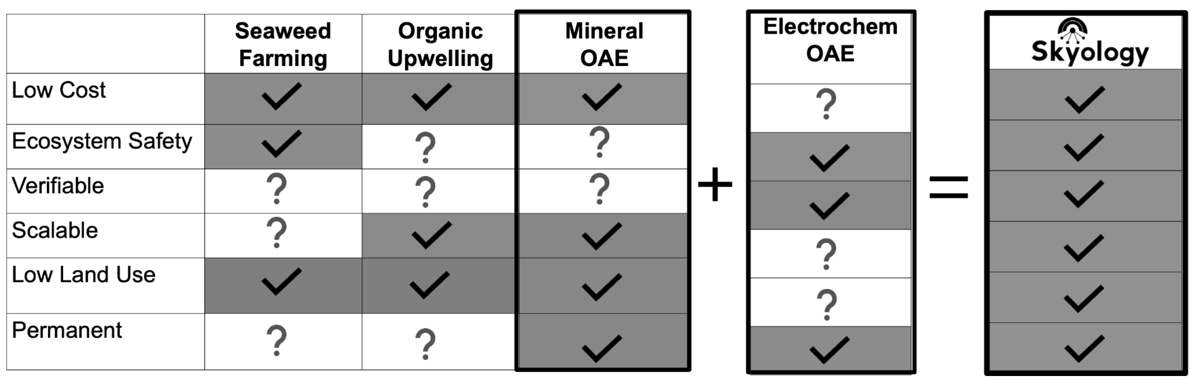

Figure 3. The Best of Engineering and Nature: An illustration of ocean-based CDR methods and key success factors.

The additional margins provided by the low-build Skyology platform give our team the resources needed to perfect monitoring, recording, and verification(MRV) before investing in production. That means more cents out of every dollar earned is invested in ocean MRV solutions. The Skyology integration process provides unique control over key ecological safety markers, total suspended solids (TSS), heavy metals, and secondary precipitations.

RFP Priorities. Skyology meets priorities in the RFP by designing crosscutting technologies that integrate into existing industries via leveraging waste streams and the call for ocean-based CDR, specifically on innovative OAE approaches. Skyology provides a uniquely controlled platform to advance MRV for all ocean-based CDR.

Reference

Bosch, T., Ph.D, & Colijn, F., Ph.D (2010). *Living With The Oceans* (1st ed., pp. 28-29). World Ocean Review. https://worldoceanreview.com/wp-content/downloads/wor1/WOR1_en_chapter_2.pdf

Tyler D. Eddy, Vicky W.Y. Lam, Gabriel Reygondeau, Andrés M. Cisneros-Montemayor, Krista Greer, Maria Lourdes D. Palomares, John F. Bruno, Yoshitaka Ota, William W.L.

Cheung. Global decline in capacity of coral reefs to provide ecosystem services. *One Earth*, 2021; 4 (9): 1278 DOI: 10.1016/j.oneear.2021.08.016

Köhler, P., Abrams, J. F., & Vo˙lker, C. (2013). Geoengineering impact of open ocean dissolution of olivine on atmospheric CO2, surface ocean pH and marine biology. *Alfred Wegener Institute for Polar and Marine Research (AWI)*, 4. https://doi.org/10.1088/1748-9326/8/1/014009

Takahashi T, Feely RA, Weiss RF, Wanninkhof RH, Chipman DW, Sutherland SC, Takahashi TT. Global air-sea flux of CO2: An estimate based on measurements of sea–air pCO2 difference. Proceedings of the National Academy of Sciences. 1997 Aug 5;94(16):8292-9.

b. **Project objectives:** What are you trying to build? Discuss location(s) and scale. What is the current cost breakdown, and what needs to happen for your CDR solution to approach Frontier's $100/t and 0.5Gt targets? What is your approach to quantifying the carbon removed? Please include figures and system schematics and be specific, but concise. Aim for 1000-1500 words.

Project Scope and Requirements

Skyology's objective is to successfully demonstrate a non-construction OAE pilot with clear system boundaries and high environmental safety in partnership with Coastal Wastewater Treatment Plants (cWWTPs). Our first system deployment has 110t(CO_2)/yr of capture capacity without adding to the existing footprint of the plant. Specific location and partnership details are included in non-public sections

A typical Skyology project is de-risked with a low-cost MRV feasibility study. Next, net negativity and price/ton are proven with man-made feedstock and then through batch testing of natural minerals with low-cost feedstock. Once MRV and mineral performance are confirmed, Skyology will use system engineering within the existing equipment of cWWTPs to optimize proven processes.

Location

Our first sites are located in areas where wildlife and agriculture have been negatively impacted by ocean acidification. Primarily focusing on the USA and Canada's west coast and the Indo-Pacific.

Requirements

1. Demonstrate effective First-of-a-Kind (FOAK) MRV sensor arrays and models in an existing alkalinity enhancement reaction. This will not be considered CDR.
    - Accurately measure pH, Alkalinity, pCO_2, DIC, and trace metals (e.g., Ni) in influent and effluent of the system.

- Accurately measure and model ocean-released pH, Alkalinity, pCO_2, and DIC metal addition. Confirm model sample size with 3rd party {C}worthy.
- Predictively model the cWWTPs for additional alkalinity for Phase 2.
- Confirm contract with MRV accounting with third-party marketplaces e.g., Vera.

2. Modify the cWWTPs system and feedstock to demonstrate FOAK with confirmed CDR.
    - Feedstock and energy consumption must be LCA carbon negative
    - Feedstock must meet trace metals and pH standards of existing WWTP permits.
    - CDR must be discounted based on the regional model confidence interval of reliable third-party [C]worthy nonprofit
    - Deliver first credits to AMC buyers
3. Optimize WWTP
    - Optimize feedstock LCA
    - Optimize variable costs
    - Complete batched test feedstock data
    - Develop standardized dashboard for stakeholders

Target Price and Scale

Requirements to meet the price goal of $122/t

- Careful vetting and selection of WWTP to choose low-build sites
- Partner with academic researchers driving innovations in alkaline materials through industry-academic grants.
- Optimize mineral environmental safety and compatibility through batch testing
- Build vendor relationships with feedstock suppliers and component producers in proximity to the site of WWTP-OAE deployment.
- Generate additional revenues from co-products of WWTP-OAE.

Requirements to meet a scale goal of .5Gt.

- Each site today an average site is capable of 1,100 - 2,000 tons/year. Today our system would require a 50% global adoption from the nearly 110,000 WWTPs to reliably deliver up .25Gt/year
- Today only 50% of global wastewater is treated (Jones et al., 2021). By 2035 we expect WWTP infrastructure investment to proliferate while India, sections of Asia, and parts of Africa will begin a middle-class population boom. North America and most of the EU have underinvested in WWTP for the past 50 years and will face an impending wall of rebuilding degraded infrastructure. As the global population welcomes its ten-billionth member, we can expect the quantity, capacity, and sophistication of wastewater treatment plants to increase rapidly. This gives skyology a growing fleet of permitted integration sites to accomplish 0.5 Gt.

Quantifying Carbon Removed

One strength of Skyology's approach is that much of our baseline monitoring and sampling is already installed at the WWTP. Every project will require field sensor installation. Having a large contained reaction means Skyology has the advantage of extremely precise carbonate chemistry changes because the reactions are taking place in a closed system. The difference in CO_2 concentrations and a corresponding increase in carbonate alkalinity give Skyology a measure of the amount of CDR that occurred in the reactor system (Rau, 2011).

We will install and monitor pH, alkalinity, and DIC through online sensors. We compile the data not only to verify removal but also to build predictive models and projections. Skyology is developing dashboards to help visualize and report to operators. These tools will combine to make important assets to WWTP and the critical reporting necessary for verification.

Skyology parters with third parties (listed section 2) to combine infield data with, carbon-centric Grid Enabled Integrated Earth system model cGENIE, and other earth system regional ocean models to validate ocean storage, durability, and long-term ecological safety.

References

Edward R. Jones, Michelle T. H. van Vliet, Manzoor Qadir, Marc F. P. Bierkens. Country-level and gridded estimates of wastewater production, collection, treatment, and reuse. *Earth System Science Data*, 2021; 13 (2): 237 DOI: 10.5194/essd-13-237-2021

Jones ER, Van Vliet MT, Qadir M, Bierkens MF. Country-level and gridded estimates of wastewater production, collection, treatment and reuse. Earth System Science Data. 2021 Feb 8;13(2):237-54.

Rau GH. CO2 mitigation via capture and chemical conversion in seawater. Environmental Science & Technology. 2011 Feb 1;45(3):1088-92. DOI: 10.1021/es102671x

c. **Risks:** What are the biggest risks and how will you mitigate those? Include technical, project execution, measurement, reporting and verification (MRV), ecosystem, financial, and any other risks. Aim for 500-1000 words.

Risk (high, medium, low)	**Mitigation Strategy**
Regulation: National regulation and local permits become more strict as OAE scales. (high)	OAE is not written into national ocean policy but could, under some coastal agreements, be considered ocean dumping. Skyology navigates the majority of regulation by having a zero-solid release system and operating within municipality effluent permits.

	Nevertheless, skyology is partnered with former UN, and Obama Administration ocean policy representatives to continue to steward and encourage protections for ocean CDR operation.
Market: Carbon Market Volatility (high)	As sales prices change and carbon markets mature. Skyology is buffering this shock by forecasting and operating under highly conservative market predictions. Furthermore, skyology is now building contracts with beachhead alkalinity customers to diversify income and increase revenue predictability.
Technical: Under field conditions, the kinetics of dissolution rates may not be as predicted by pilot experiments or modeling. (low)	Site selection: Skyology selects sites that were previously tested for various chemical and mineral dissolution rates. This way, we begin each project with years of proxy data. Feedstock selection: Skyology will modify batch or continuous reactions to find the optimal feedstock blend between anthropogenic materials and minerals. Grain Size: Adjusting material mix ratios and surface area to optimize kinetics.
Regulation: Preexisting permits can have stringent effluent parameters (low)	Skyology vets each existing permit for tolerance for additional alkalinity and total suspended solids (TSS). Valves and mix ratios within the closed system accommodate batch testing and precise adjustments of effluent. Back-up buffer systems and procedures are installed with synthetic materials to balance effluent in case of catastrophic failure. As a last resort reactors are taken offline and restarted without disrupting the flow rates needed to maintain WWTP operations.
Technical: Under field use conditions sensors will be damaged more frequently and need replacing. (medium)	Stress-testing sensors for short field trials, although we know sensors will have a shorter field life. Including backup sensors and manual sampling-ports can keep the reactor operational in case online sensor of failure.

Ecosystem: Ocean health impacts (medium)	Skyology is engaging with existing regional experts and stakeholders to establish ecosystem baseline conditions. Furthermore, containment and measurement of inputs and outputs will ensure we do not exceed agreed-upon local pH, ALK, and metals. Feedstock selection is the most reliable way to avoid any unwanted release. Impurity measurement will be applied multiple times per batch.
Operational: Supply chain, Feedstock price, transportation price increases (low)	Skyology is building a network of diversified feedstock suppliers. At scale, Skyology will employ just-in-time delivery to avoid high inventory and working capital. Our system is a multi-material OAE operation. Skyology selects materials that are the best regional fit. Reliving our reliance on a single material will curb supply shortages.
Operational: Moving heavy and fine feedstock will pose employee risks. OHS risk. (medium)	Skyology is developing material handling protocols, including proper industrial and personal equipment. Providing OHS training required by all technicians. Fine materials will be covered. Airborne particle monitors will be present in loading areas.

d. **Proposed offer to Frontier:** Please list proposed CDR volume, delivery timeline and price below. If you are selected for a Frontier prepurchase, this table will form the basis of contract discussions.

Proposed CDR over the project lifetime (tons) *(should be net volume after taking into account the uncertainty discount proposed in 5c)*	1000t
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	Dec 25, 2026,
Levelized Price (\$/ton CO_2)* *(This is the price per ton of your offer to us for the tonnage described above)*	\$980/ton CO_2

** This does not need to exactly match the cost calculated for "This Project" in the TEA spreadsheet (e.g., it's expected to include a margin and reflect reductions from co-product revenue if applicable).*