

# Banyu Carbon

## 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

Banyu Carbon

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

Seattle, WA

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

Alex Gagnon and Julian Sachs

Brief company or organization description <20 words

We capture carbon with light while generating carbon-negative electricity. The resulting high-quality carbon credits are easy to verify.

#### 1. Public summary of proposed project<sup>1</sup> to Frontier

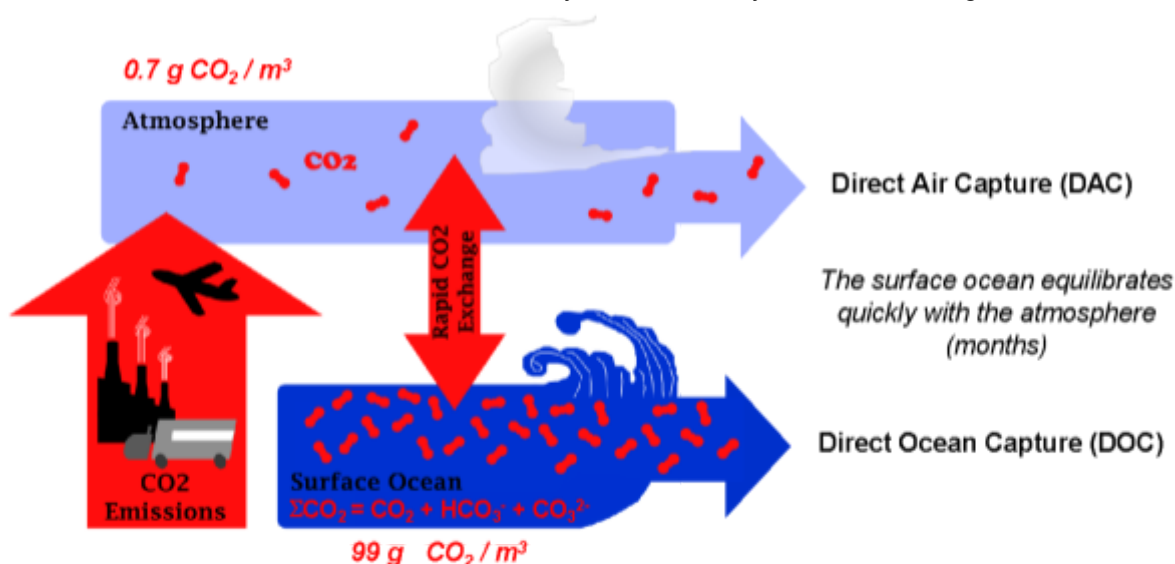
- a. **Description of the CDR approach:** Describe how the proposed technology removes CO<sub>2</sub> from the atmosphere, including how the carbon is stored for > 1,000 years. Tell us why your system is best-in-class, and how you're differentiated from any other organization working on a similar approach. If

---

<sup>1</sup> 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.

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.

Our fundamentally new approach to carbon dioxide removal combines two enabling concepts. First, it uses seawater as a carbon source instead of air. Seawater naturally concentrates  $\text{CO}_2$  from the atmosphere. Removing this carbon from the surface ocean withdraws a commensurate amount of  $\text{CO}_2$  from the air because of rapid equilibration (**Fig. 1**). Unlike the atmosphere, where  $\text{CO}_2$  is a trace component, dissolved  $\text{CO}_2$  and its hydrated and deprotonated forms (collectively, dissolved inorganic carbon or DIC) is more abundant in seawater than all other dissolved gases. The greater abundance of carbon in seawater fundamentally shifts thermodynamic and scaling issues of CDR.



**Fig. 1:** Removing  $\text{CO}_2$  from the surface ocean is equivalent to capturing it from air owing to rapid gas exchange between these two reservoirs (on the timescale of months). Keeping global temperatures  $<2^\circ\text{C}$  above preindustrial will require removal of 1-10 Gt  $\text{CO}_2/\text{yr}$  from the combined ocean-atmosphere system.

The vast amount of  $\text{CO}_2$  locked in seawater remains dissolved if it stays near neutral pH, but outgases spontaneously when acidified. The second enabling concept in our process is the use of a light-triggered reversible photoacid as a low energy means to extract and concentrate  $\text{CO}_2$  from seawater. We use these reversible photoacids to temporarily acidify seawater and remove  $\text{CO}_2$ . The merocyanine photoacids at the heart of our process change their structural conformation (i.e., isomerize) when exposed to visible light (Berton et al., 2021; Liao, 2017; Wimberger et al., 2022). The “activated” or “excited” species then spontaneously undergoes ring closure to form a spiropyran with the release of a proton. The acidity constant ( $\text{pK}_a$ ) of our improved photoacid in the dark is about 8.7 while that of the light-activated species is about 4. The resulting increase in acidity upon illumination provides the proton driving force for our carbon capture process.

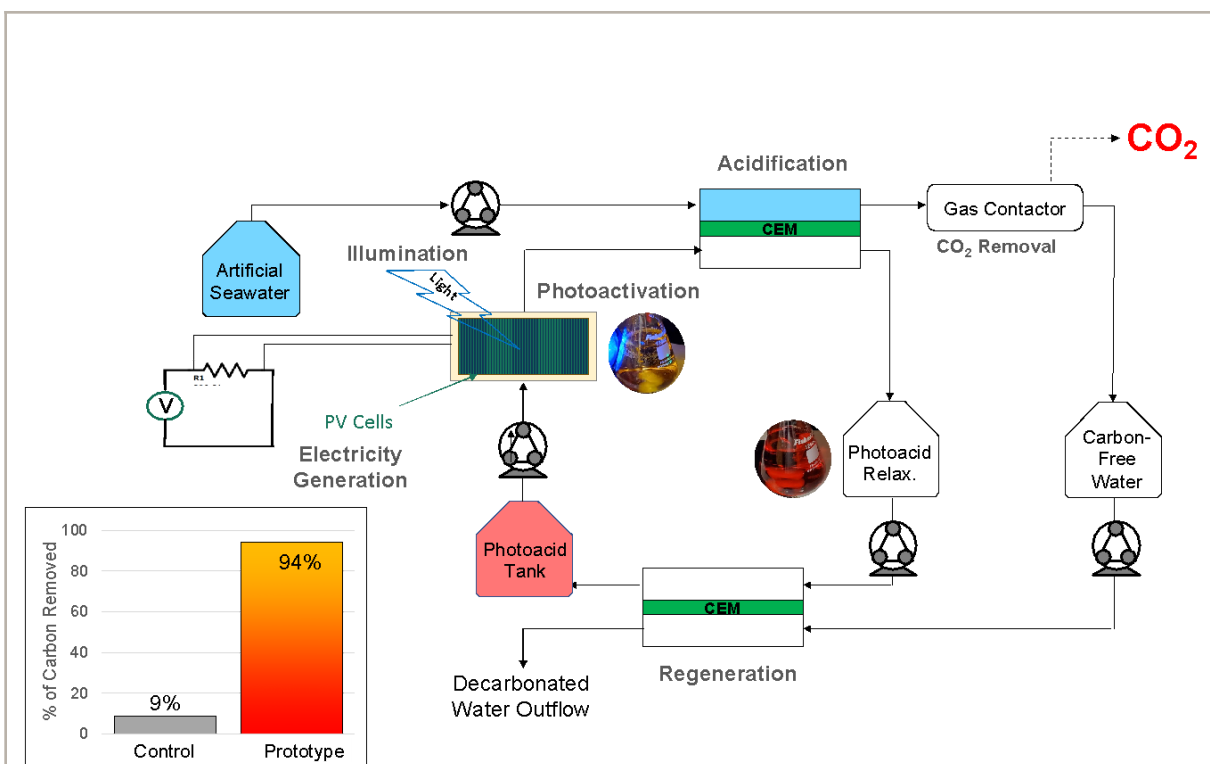
Other approaches to CDR create strong chemical bonds so they can bind to trace amounts of carbon in the atmosphere. Liberating  $\text{CO}_2$  from these bonds requires large inputs of energy and

associated carbon emissions. Direct carbon capture from seawater using state-of-the-art electrochemical approaches (de Lannoy et al., 2018; Digdaya et al., 2020; Eisaman et al., 2018) also has high electricity demands. Instead of these energy intensive approaches, our process directly couples sunlight to seawater-based CDR. Using our current technology, our process is estimated to require 90% less energy than competing direct seawater carbon removal processes and 30% less energy than best-in-class direct air capture processes. But since it converts the sunlight not required for photochemistry and carbon removal to electricity with embedded solar cells the process generates far more electricity than it uses.

During the first step of the chemical cycle at the heart of our process (**Fig. 2**), visible light from the sun excites reversible photoacids to release protons. These protons acidify seawater, lower seawater pH, and shift the dissolved carbon into CO<sub>2</sub> gas. This CO<sub>2</sub> gas is removed from seawater by rapid, passive diffusion across a gas contactor membrane. We have conducted extensive lab and field tests under relevant seawater flow rates to show that this diffusion step does not require exotic membranes or high pressures and can be attained using off-the-shelf components (Gagnon et al., in review). Meanwhile the photoacid is pumped into the dark where it spontaneously relaxes back to its more basic form. The cycle is completed when the now basic photoacid is regenerated using spent seawater. Seawater is then returned to the ocean with CO<sub>2</sub> removed, but otherwise unchanged. In net, this process will produce CO<sub>2</sub> gas from seawater using the power of light. The decarbonated seawater that is returned to the ocean has the added benefit of counteracting ocean acidification locally.

**Fig. 2:** Our patent-pending process is designed to use seawater and sunlight as part of a low energy method to capture CO<sub>2</sub> for subsequent sequestration or utilization. We convert the high concentration of dissolved carbon in seawater (DIC) to CO<sub>2</sub> with light-activated photoacids, followed by diffusion across a gas contactor membrane. The CO<sub>2</sub> product can be used as is or pressurized and purified to levels required for different sequestration processes. By co-locating with facilities that pump and discard large volumes of seawater, such as power and desalination plants, or utilizing tidal or river currents to provide the necessary pressure head, the energy and cost expenditures associated with pumping water can be further reduced and a waste stream can be converted into a green revenue stream.

Our lab prototype of the system removes 94% of the carbon from a flowing artificial seawater solution. A process diagram of this system is shown in **Fig. 3**. We have continuously run the benchtop prototype for 15 hours, removing 19 mg CO<sub>2</sub> and successfully demonstrating that the photoacidification, CO<sub>2</sub> removal, and photoacid regeneration steps all operate as designed. While modest in scale, this important proof of concept shows that we have developed a viable carbon removal process that behaves as modeled. A hallmark of our system is that the photoacid loop is closed. It is kept separated from the seawater and can be activated and deactivated 14,000 times before its effectiveness decreases by 50%.



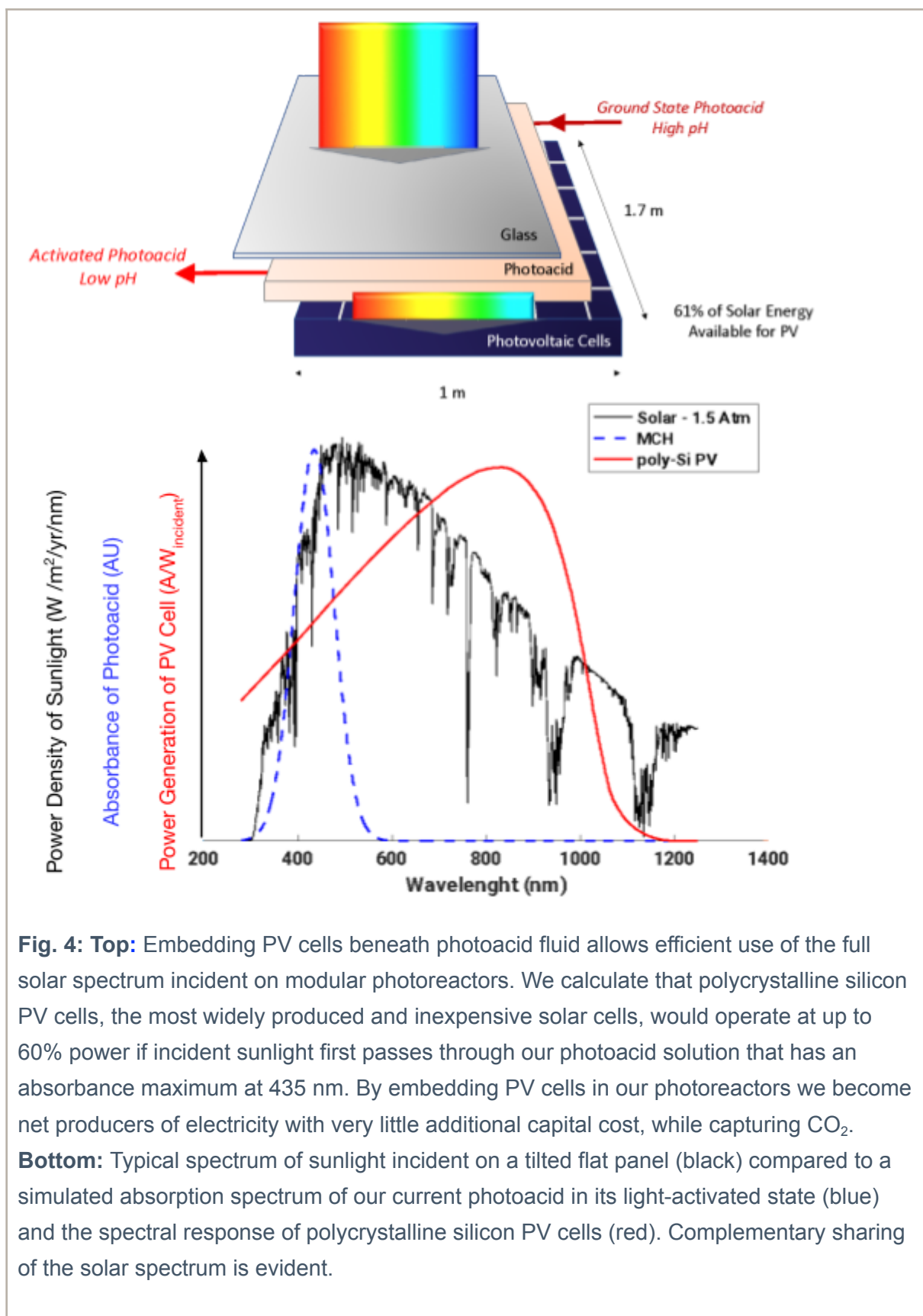
**Fig. 3:** Flow diagram of our benchtop prototype that successfully demonstrates photoacidification, gas removal, regeneration, and electricity generation. This system removes 94% of the carbon from the artificial seawater pumped through it, demonstrating that the process works as modeled. Cation exchange membranes (CEM) are used to transfer protons between photoacid and seawater solutions. Because the photoacid is photochromic its color in the dark (red) differs from its color under blue light (yellow; see photos in center of image), a useful property since it results in little or no self-shading. Because only a small region of the visible light spectrum is absorbed by the photoacid solution, most of the sunlight passes through it and is used to produce electricity (771 kWh/ton CO<sub>2</sub> removed) with inexpensive polycrystalline Si photovoltaic cells beneath the photoreactor.

Because the photoacid only absorbs a portion of the solar spectrum, the light passing through it can be used to generate electricity by embedding photovoltaic (PV) cells underneath the photoacid fluid (**Fig. 4**). This implementation allows efficient use of sunlight incident on modular carbon collectors (**Fig. 5**). We calculate that polycrystalline Si solar panels, the most widely produced and affordable solar PV material, will generate 60% of its maximum expected power when placed below our photoreactors. Because our photoreactors are already designed to collect sunlight, the marginal cost of these solar cells is small and requires no additional land. However, the benefit is large. By embedding PV cells in our photoreactors we can produce more electricity than our process consumes while simultaneously removing carbon. The land use for our approach is small when compared to the need for competing processes to add large captive solar or other alternative energy facilities for energy. Our technoeconomic modeling of a photoacid-based carbon removal process indicates that by the mid-2030s, a profitable carbon removal facility could operate at the scale of

hundreds of millions of tons per year with a levelized cost of less than \$60/ton CO<sub>2</sub> while producing a surplus of more than 25 GWh yr<sup>-1</sup> photovoltaic electricity.

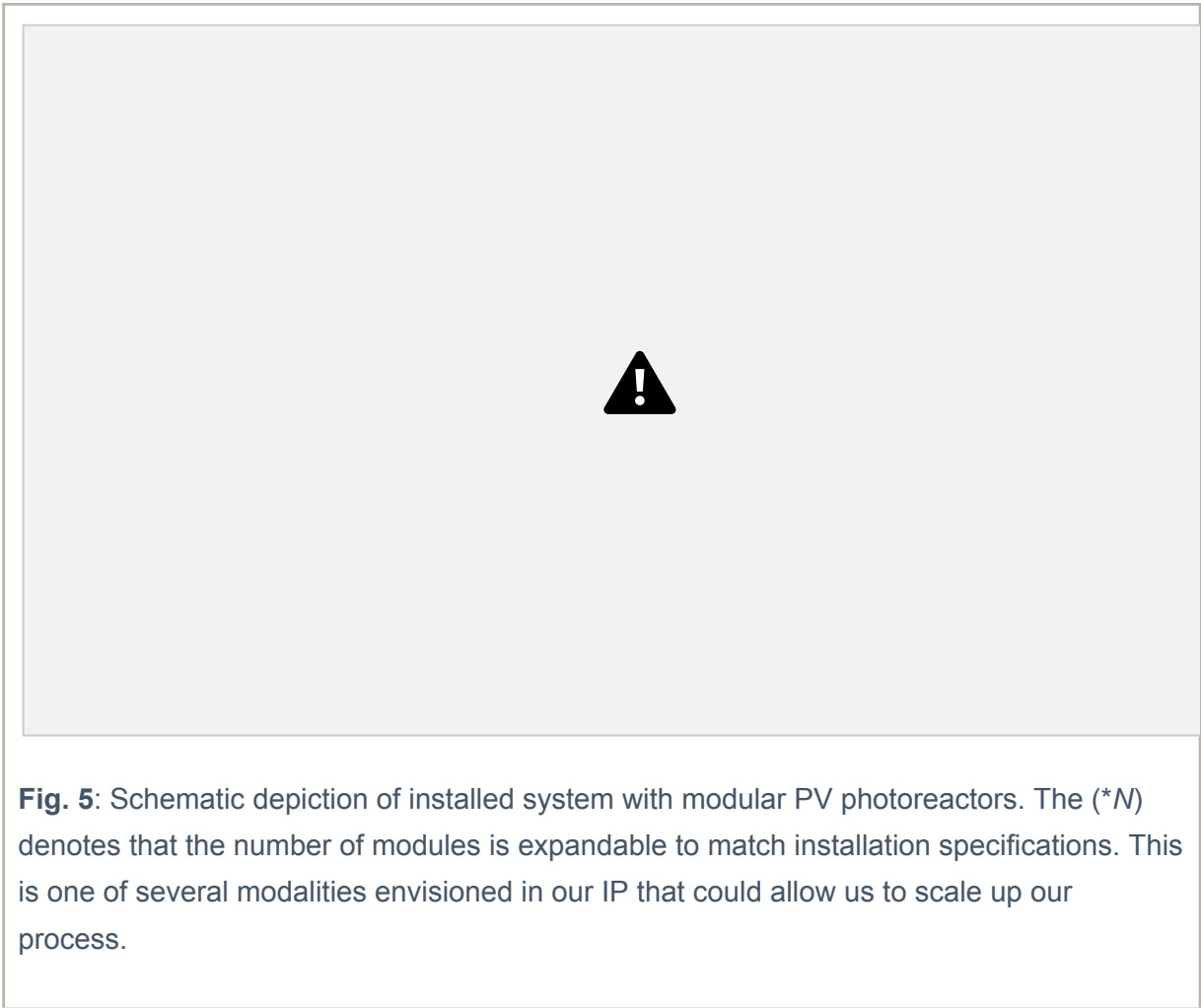
One way to minimize plumbing in future large systems that we plan to explore is the use of solar concentration. Systems based on linear Fresnel or parabolic concentrators that achieve a concentration factor of 20-40 would require roughly 3-6% the amount of photoreactor hardware and piping. Much of the solar collection area is instead covered by relatively cheap mirrors, with a single length of photoreactor roughly every 40 m. The heat generated from this magnitude of solar concentration is projected to be modest, and is easily removed by the large flow of seawater. Moreover, the resulting warming of the seawater provides an efficiency boost since warmer water degases CO<sub>2</sub> more readily.

Banyu Carbon focuses on carbon capture because it represents >85% of the cost, and most of the complexity, of direct carbon removal. The transport and geological storage of CO<sub>2</sub> is a well-established technology used in the process of enhanced oil recovery. Millions of tons of fossil CO<sub>2</sub> are extracted, transported, and injected into petroleum reservoirs per year in the US today. Our process produces a pure stream of gas and surplus electricity. We budget for the compression of the CO<sub>2</sub> to supercritical, its transport through 1,000 km of pipeline, and permanent storage in geological reservoirs. The latter can be depleted petroleum reservoirs, saline aquifers, or basalt formations. For this project, the CO<sub>2</sub> we produce can be incorporated into concrete via carbon mineralization reactions that convert it into rock for permanent storage.



**Fig. 4: Top:** Embedding PV cells beneath photoacid fluid allows efficient use of the full solar spectrum incident on modular photoreactors. We calculate that polycrystalline silicon PV cells, the most widely produced and inexpensive solar cells, would operate at up to 60% power if incident sunlight first passes through our photoacid solution that has an absorbance maximum at 435 nm. By embedding PV cells in our photoreactors we become net producers of electricity with very little additional capital cost, while capturing  $CO_2$ .

**Bottom:** Typical spectrum of sunlight incident on a tilted flat panel (black) compared to a simulated absorption spectrum of our current photoacid in its light-activated state (blue) and the spectral response of polycrystalline silicon PV cells (red). Complementary sharing of the solar spectrum is evident.



- 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.





m<sup>3</sup>/day) of surface seawater, has a master use permit, has high solar energy potential, has over 800 acres of seaside land for short-term rental to research and business entities, and has dozens of acres of shallow flumes and ponds for rent. In addition, Hawaii has the highest electricity rates in the country and the local utility pays \$0.19/kWh for electricity sold back to the grid, an important revenue stream for us.

**Fig. 6:** Satellite image of NELHA in Kailua Kona, Hawaii, the proposed site of Banyu Carbon's 360 tCO<sub>2</sub>/yr Commercial Demonstration plant. This marine technology park pumps 56,000 Gal/min of surface seawater for use by research and commercial enterprises that rent space, and has a Master Use Permit in place that will cover our operations. Several dozen acres of shallow ponds and flumes are available that we will use to quantify the uptake of atmospheric CO<sub>2</sub> and establish our MRV protocol.

A flow diagram of the main plant components is shown in **Fig. 5**. We will remove 360 tons of CO<sub>2</sub> with this facility and that CO<sub>2</sub> will be permanently sequestered in concrete by partnering with local concrete producers, three of whom we have spoken with. This demonstration in itself will be a significant step forward for carbon removal, as it will be about a tenth the size of the largest existing direct carbon removal facility, ClimeWorks' Orca Plant in Iceland. But more importantly, it will lay the groundwork for rapid scale up to a 10,000 tCO<sub>2</sub>/yr light-driven and electricity-producing ocean CDR facility in 2027, and >1 MtCO<sub>2</sub>/yr capacity by 2030.

The total levelized cost per ton of CO<sub>2</sub> removed and permanently stored with this Commercial Demonstration Plant is \$1,318, \$267 of which is CapEx and \$845 of which is OpEx. Notably, energy cost is *negative* \$17 per tCO<sub>2</sub> because our process produces electricity that will be sold to the grid.

The next generation plant that will be capable of removing 10,000 tCO<sub>2</sub>/yr and should be operational in 2027 will have a substantially lower total levelized cost of \$199/tCO<sub>2</sub>, of which \$125 is CapEx and \$31 is OpEx. The cost reductions stem primarily from improved component and consumable costs at scale, improved photoacid characteristics, and spreading personnel costs over a larger plant. There is a clear path to reaching <\$100/tCO<sub>2</sub> by the time we reach the scale of 1 MtCO<sub>2</sub>/yr with modest economies of scale.

Importantly, this first commercial demonstration will play a key role in demonstrating MRV for our technology as well as for direct carbon removal approaches in general. Our MRV will be conducted by equilibrating the low-carbon seawater we produce with the atmosphere in shallow ponds. The 3-5 day residence time of water in these ponds will be sufficient for us to measure the uptake of CO<sub>2</sub> from the atmosphere, which must be verified in order for direct ocean CDR to be accepted as a viable CO<sub>2</sub> reduction strategy.

In addition to storing the CO<sub>2</sub> we capture in concrete (ex-situ carbon mineralization) there is a possibility that in-situ mineralization will be a viable alternative. The geology of Hawaii is very similar to that of Iceland where CarbFix and affiliated researchers have demonstrated permanent CO<sub>2</sub> sequestration in the island basalt, and research and test wells on Hawaii show great promise for large-scale CO<sub>2</sub> sequestration (DePaolo et al., 2021). Our process yields CO<sub>2</sub> that can be easily made to any purity and/or compressed to supercritical, so we are flexible with regards to carbon storage partner.

- 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.

**TECHNICAL & EXECUTION RISKS:** We have successfully demonstrated our carbon capture process works at the lab scale, but challenges will arise as we scale up. Main risks include:

(1) Cost and longevity of the photoacid. Our current version of the photoacid is synthesized in three steps from inexpensive starting materials and contains no metals or rare elements. Its structure is very similar to a common red dye used in plastics and textiles that is produced at the rate of tens-of-thousands of tons per year at a cost of \$10-20/kg. We assume that the cost of production of our photoacid will be similar once we are manufacturing it at the 100+ kg/yr scale but there is a risk that manufacturing costs will be higher than this and therefore add to OpEx. The current version of our photoacid has a half-life of 10 days under present operating conditions, which allows it to be cycled 14,000 times. We assume we can increase its longevity to 30 days within the next 2 years. With that longevity we will require 0.44 kg photoacid/ton CO<sub>2</sub>/yr capacity. If we cannot increase the longevity of the photoacid beyond the 10 days of the current version it will increase OpEx somewhat. Fortunately, the degradation mechanism is known and it causes the photoacid molecule to split into two pieces that are the same two pieces that are combined in the third and final step of the photoacid synthesis. We have demonstrated in the lab that the two pieces can be easily recovered from the photoacid working fluid, then recombined to produce recycled photoacid. We don't assume this will be necessary, but if costs of this recycling process are less than costs of synthesizing fresh photoacid we will pursue it at the industrial scale. Burgeoning research on photoacid structure-function relationships suggests that either the needed hydrolytic stability or the development of a large-scale process to recover and replenish degraded photoacid is achievable within the next 1-2 years.

(2) The cation exchange membranes (CEMs) used in our lab prototype are effective but costly for commercial use and must be eliminated in order to bring total levelized costs of our CDR process below \$100/ton CO<sub>2</sub>. Fortunately, our process is gentler than the main applications of these membranes in fuel cells and electrochemical applications that often require ion specificity, stability against high temperature, strongly reducing, or strongly oxidizing conditions. We have developed three different modalities that eliminate CEMs, all of which are viable at the lab scale but have not yet been tested under continuous conditions in the field or at large scale. The 10 tCO<sub>2</sub>/yr pilot and 360 tCO<sub>2</sub>/yr commercial

units will be built with the simplest and lowest cost option that involves ion exchange resin beads that are charged with protons during daylight hours and discharged to acidify seawater and drive off CO<sub>2</sub> during the night. This approach has the added benefit that we can operate the seawater acidification and CO<sub>2</sub> gas removal portions of our facility 24 hours a day instead of just during daylight hours, which reduces pump sizes and other capital expenses.

**ENVIRONMENTAL RISKS:**

- (1) Impact to larval fish and invertebrates from seawater pumping. Large-scale pumping of seawater is presently conducted by power plant operators and desalination facilities globally. These facilities pose risks to marine life through impingement (suction against intake screen) and entrainment (passage through intake screen). These risks can be ameliorated with the use of intake wells and infiltration galleries that allow water to be drawn through the seabed rather than the open water. Although this risk to marine life from pumping seawater is not unique to our CDR process, we will need to work closely with environmental protection agencies to ensure our seawater pumping infrastructure is as benign as possible to marine biota.
- (2) The toxicity of our photoacid is not known. Our process keeps the photoacid fluid separated from seawater but there is some risk that small amounts of it could be released into the ocean. In practice there is little or no risk of even this low-level contamination occurring since our photoacid will be anchored to a substrate. This has already been de-risked and works well in the lab. Furthermore, the part of the photoacid molecule anchored to the substrate will result in the known degradation path of the photoacid losing a non-toxic molecule that is an FDA approved food flavoring agent to the seawater. We have a plan to attach both sides of the photoacid to the substrate, in which case neither of the two degradation products would be lost to seawater. There is risk that this will not be successful but there are multiple examples in the peer-reviewed literature of very similar photoacid molecules being anchored to a solid substrate so the risk of not being successful is low.

**FINANCIAL RISKS:** A key risk is that markets for carbon removal and CO<sub>2</sub> product may be slow to develop. The direct CO<sub>2</sub> removal market is miniscule at present (~10 kton CO<sub>2</sub>/yr) and will have to grow massively for the financial success of this sector. The recent US Inflation Reduction Act established an up to \$180/ton (45Q tax) credit for directly captured and sequestered CO<sub>2</sub>, which promises to make CDR with our technology profitable. In the

near term this risk could be mitigated by securing industrial CO<sub>2</sub> users that mineralize CO<sub>2</sub> into rock, such as concrete manufacturers.

An additional market risk is that a cheaper and less energy intensive carbon capture technology will be developed. Theoretical calculations indicate that our process should be competitive when compared to DAC and seawater electrolysis systems but real-world tests must verify this. The scope and scale of the CDR opportunity is so massive, and the maturity of the technology so nascent, that there will likely be opportunities for several technologies to gain traction in the marketplace.

**MRV RISKS:** Direct removal of CO<sub>2</sub> from surface seawater lowers atmospheric CO<sub>2</sub> only after the surface water from which CO<sub>2</sub> has been removed re-equilibrates with atmospheric CO<sub>2</sub>. For most of the ocean this occurs within months, based on decades of oceanographic measurements and modeling studies. The CO<sub>2</sub> we remove from seawater is easily measured once we produce a pure stream of CO<sub>2</sub> gas. Verifying the amount of atmospheric CO<sub>2</sub> that gets drawn into the ocean as a result of that removal will need to rely in part on regional ocean scale (ROMS) models that incorporate the carbonate chemistry. Many such models exist but we will likely need to partner with academic researchers to apply them in the locations we deploy our CDR technology. In the more immediate term we will conduct our own measurements of CO<sub>2</sub> uptake from waters we have decarbonated using small ponds through which our decarbonated seawater flows. We have extensive experience measuring carbon concentrations in seawater and have the instrumentation needed to do this routinely.

**EQUIPMENT RISKS:** Although we have several cost reduction strategies that we believe are viable, there is no guarantee that we can reduce the costs of components low enough for cost-effective adoption of our CDR process. Durability, resistance to corrosion, and biofouling of system components will also be assessed prior to and during our pilot deployment. As seagoing chemical oceanographers with decades of combined experience building and deploying oceanographic equipment we are well aware of the challenges associated with biofouling and corrosion. We know what the risks are and how to mitigate them.

- 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.

<b>Proposed CDR</b> over the project lifetime (tons) <i>(should be net volume after taking into account the</i>	360 tons
--	----------

uncertainty discount proposed in 5c)

**Delivery window**  
(at what point should Frontier consider your contract complete? Should match 2f)

By end of 2026

**Levelized Price (\$/ton CO<sub>2</sub>)\***  
(This is the price per ton of your offer to us for the tonnage described above)

\$ 1,350

\* 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).

