Bloomineral

Carbon dioxide removal prepurchase application

Summer 2024

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 2024 summer purchase cycle. Include as much detail as possible but omit sensitive and proprietary information.

Company or organization name

Bloomineral

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

France

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

Caroline Thaler, Julien Danzelle

Brief company or organization description <20 words

Bloomineral removes CO_2 from the air and mineralizes into valuable construction material through a biological process known as biomineralization.

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. 1000-1500 words

At Bloomineral, we developed a way to remove CO_2 from the air and turn it into pure limestone ($CaCO_3$) through biomineralization. This happens where seawater and air meet, using a chemical balance created by adding alkaline materials to the seawater. The CO_2 dissolves in the seawater and becomes

[1] We use "project" throughout this template, but the 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.

bicarbonate (HCO_3^-) ions. Marine organisms then combine those dissolved CO_2, bicarbonate, and calcium ions present in seawater into biominerals.

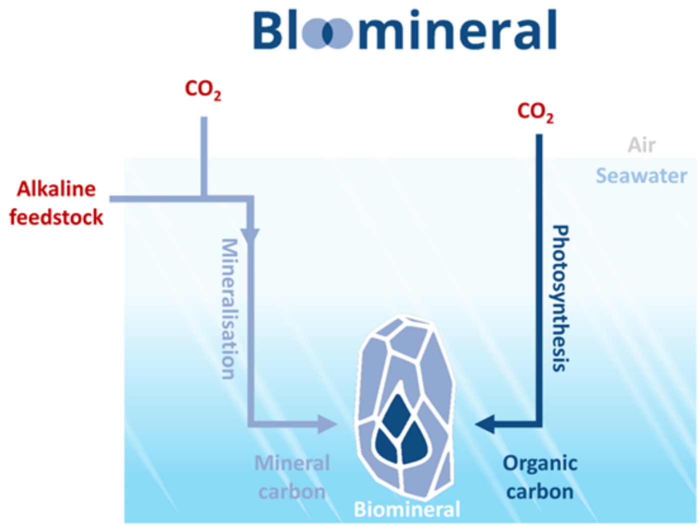

Figure 1. Simplified illustration of our process combining alkalinity enhancement with photosynthesis and mineralization to sequester CO2 into biominerals

Our biominerals are made up of pure $CaCO_3$ crystals (80-85%) plus organic fibers coated with $CaCO_3$ crystals (15-20%). These materials have properties that make them a good substitute for cement, eventually becoming part of concrete, and reducing hard to abate emissions.
Our process stores CO_2 into $CaCO_3$ crystals for over 10 000 years. It's likely that the CO_2 in the crystal coated fibers is also stored permanently, for over 1000 years, when removed from seawater and sealed in concrete.
By integrating CO_2 removal and biomineralization, we harness the maturity and fast scalability of biobased CO_2 removal with the permanence of mineral sequestration.

We also generate a new type of biomaterial capable of accelerating the cement industry's transition to a low-carbon future, one with the hardest to abate emissions (and energy consumption). Our process demonstrates that the production of construction material with valuable properties can be carbon negative and energy efficient.

In doing so, we offer 4 main advantages:

1. **Energy Efficiency**: Unlike any other marine biomass, our calcified organisms contain only 10 to 15% water, significantly reducing the need for drying. In addition, we use the entire organism, avoiding the need to extract molecules and simplifying the process.
2. **Low Nutrient Requirements**: Our calcifying organisms require up to 5 times less nutrients than any phytoplankton. This provides our cultures extremely low risk of competition with fungi and bacteria and allows us to work in non-sterile, open systems, reducing capex and opening the way of atmospheric CO_2 removal for calcifiers.
3. **CO2 Capture and Alkaline Feedstock Utilization**: We capture CO_2 directly from the air at low concentration, reducing the risk of CO_2 leaks and enabling easy monitoring of all inputs and outputs. The alkaline feedstock can include concrete waste, alkaline rocks, and salt-rich alkaline wastes unsuitable for ERW on agricultural land due to their

high level in salts. Our calcifiers, working at seawater concentration, fully dissolve the alkaline feedstock, ensuring complete carbonatation. These features give Bloomineral the potential to achieve a CO_2 removal rate of 0.5Gt per year.

4. **Material Quality and Market Integration**: Our product is pure limestone, compliant with cement norms, when separated from the organic carbon fibers. Our $CaCO_3$ crystals are chemically pure, and mineralogically uniform due to genetic control. This provides us an easy go to market pathway. When we maintain the crystals and the mineral coated fibers together, we obtain a new material with useful properties that could replace other fibers like asbestos.

We address several identified priorities:

Industrial integration and Additional revenue sources

Our method generates additional revenue by converting waste into commercial valuable pure limestone. This limestone has useful properties, is already compliant with cement norms, and can be integrated like regular limestone in industrial processes. Limestone powder is already a tool to decarbonize concrete, by replacing up to 20% of cement without affecting the material properties of concrete. A cementitious limestone powder could push further the substitution and generate even more CO_2 emissions reduction.

Environmental / economic co-benefits

Our environmental benefits come from an alternative use of our limestone. Currently, 500 000 tons of biominerals are dredged annually from the ocean floor for agricultural lime, water treatment, and animal feed. This practice harms slow-growing coralline algae reefs off Norway, Brazil, Wales, and France. We propose replacing this with our sustainable biominerals. When used correctly, after raising soil pH with non-carbonated alkaline rocks, our nutrient-rich biominerals can support regenerative agriculture without losing their captured CO_2. Although this application is not our primary focus due to the need for further carbon flux monitoring, we believe this could have a tremendous environmental positive impact on these natural ecosystems and soil health.

BiCRS innovation

Our BiCRS innovation lies in the sequestration method of the organic phase. There is no doubt photosynthesis must play a role in human driven CDR approaches, but the timeframe of CO_2 release when organic carbon degrades threatens our future carbon budget.

We take inspiration from geologic history, where organic carbon preservation over millenia happens when it is sequestered at the micrometric scale, inside crystals. Our organic carbon consists of refractory fibers coated with carbonate crystals, protecting it from microbial degradation. Additionally, using our biominerals in concrete provides extra CO_2 preservation in case of organic carbon degradation: Organic carbon converted into CO_2 in concrete reacts with free lime (CaO) to form new $CaCO_3$ crystals, which fill pores and cracks, which is the principle of concrete self-healing properties. This needs further demonstration and quantification but could be a new way to sequester organic carbon safely.

EW innovation

We solve the conundrum of alkalinity carbonatation, that requires water, and the recovery of crystals, that necessitates separating and dry crystals, which is energy consuming. Our biological, non-sterile system enhances weathering of non-soluble waste particles. One key factor in dissolution is media saturation. Our organisms actively pump calcium out of seawater, accelerating the dissolution of calcium-rich waste particles like concrete or soda ash. Additionally, in the specific use case of our biominerals as Aglime, the high solubility level of our crystals (both for mineralogical and size crystals reasons) makes them excellent ERW feedstock in comparison to traditional limestone, which will benefit agricultural practices.

mCDR innovation

Despite scarce attempts at using Biomineralization yet, it is the most efficient mCDR tool used by the earth and exactly what constitutes its carbon pump : the combination of alkalinity runoff from the continent, allowing the formation of calcium carbonates associated to biomass, that then sinks to the bottom of the ocean and stays trapped in sediments. In our efforts to mimic this process, we believe sinking must be avoided to avoid perturbation of deep ecosystems and have the possibility to use these minerals with great properties. However, biomineralization poses challenges that we believe we can solve:

Unlike calcifying phytoplankton we do not need photobiorectors to obtain dense cultures, unlike other highly productive calcifiers like corals, our organisms can sustain important environmental variation (salinity, temperature, metal levels) that sets them as perfect bio auxiliaries to work with alkaline wastes. Finally, unlike many calcifiers that are filtering organisms, ours are photosynthetic, their overall carbon impact is thus higher and it adds energy efficiency as the water currents in our farms can be maintained minimal.

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 cost and scale criteria?[2] What is your approach to quantifying the carbon removed? Please include figures and system schematics and be specific, but concise. 1000-1500 words

We are pioneering a new circular way to generate carbon negative construction materials, directly on industrial sites. Considering our process uses mainly seawater and alkaline feedstock generated by industries, we must deploy our farm on the seashore, guided by the principles of industrial symbiosis. Our first farm will be co-located with industries that both generate alkaline feedstock and serve as our first clients for our biominerals.

We are selling the first 350 tons of CO_2 removed from the atmosphere, mineralized and sold to be sequestered in concrete from our pilot project. This pilot, an onland marine farm, will scale to full capacity by 2027. The total CO_2 removal and mineralization at each site will largely depend on the number of culture modules installed and the pace of biomineralization, which will accelerate with our ongoing domestication efforts and strain selection producing results. One can think about calcifying organisms as sorbents in a DAC factory that could continuously self replicate and improve, without changing the surrounding hardware.

In 2027, the pilot should remove approximately 1000 tons of CO_2 (the year of most modules deployment). The following year, with all modules fully operational, it should achieve 2500 tons of CO_2 removal. When our technology is mature, that same site is expected to generate an annual removal of 6300 tons.

Our modules deployment will begin in 2025 once funding is secured, with operation starting in 2026. The farm will expand annually to support our organisms' doubling time pace. The propagation of our calcifying organism follows an exponential growth pattern, requiring two years (2025-2027) for initial

[2] We're looking for approaches that can reach climate-relevant scale (about 0.5 Gt CDR/year at $100/ton). We will consider approaches that don't quite meet this bar if they perform well against our other criteria, can enable the removal of hundreds of millions of tons, are otherwise compelling enough to be part of the global portfolio of climate solutions.

expansion. Our installation will be covering just over 1 hectare by 2027. Yield per site will increase after 2027 as we refine domestication, aiming to match the growth rates of domesticated macroalgae. The farm has significant expansion potential, with up to 100 hectares of available industrial land at each location, often in areas with a history of intense industrial activity.

We are selling our removal and mineralization pathway for 350 tons at 1428$/ton. The breakdown of these costs are :

- Opex: 22% dominated by the cost of labor
- Energy: 34% (for a mix of grid and PV)
- Capex: 44% dominated (beyond the cost of capital) by equipment

To reach the Frontier target of 100$/ton for the removal and mineralization we will improve our energy and capex costs in priority, and help our labor costs with some automation. What is also going to have tremendous down-costing effect is the following lever: Improving biomineralization pace, by improving our domestication and propagation techniques, having repeated harvest, and strain selection, all of the costs (capex/opex/energy) are going to be optimized simultaneously.

In addition we have a co-revenue: By selling the limestone and considering there is approximately 0.65 ton of CO_2 sequestered per ton of limestone (both as mineral and organic carbon):

1$ per limestone unit = 1.53$ per CO2 unit.

Currently, limestone microfiller without specific properties, quarried traditionally, carbon neutral (approximately 0.070 tCO2/ton) costs around 85$/ton. This brings, without a green premium on the cost of the material, an additional revenue of 130$/ton of CO_2 mineralized. Our target is thus to reach 230$/ton for CO_2 removal and mineralization into cementitious limestone and we believe we can reach that target at scale, with an energetic consumption of 0,9 MWh/ton of cementitious material produced.

Regarding scale, reaching 500 Mt/y of CO_2 removal will require to source enough alkaline feedstock. We have the advantage of being able to tackle both dried and wet alkaline sources, as well as salt-rich alkaline sources. This flexibility is a huge advantage as many ions (magnesium, sulfates, phosphates) are chemical inhibitors of pure $CaCO_3$ crystal formation. Another opportunity lies in the fact that our calcifying organism can accumulate metals in the mineral lattice and tolerate high levels of “pollution”. This capability gives us the opportunity to develop solutions for tackling alkalinity sources with problematic high metal levels.

The three main type of alkalinity sources we consider for our system are:

- **Concrete and cement waste/Demolition waste**

These wastes are generated in gigatons yearly (0.5 Gt just in Europe) and will have the potential to be used to remove more than 1 Gt of CO_2 yearly by 2040

- **Soda ash waste (salt-rich alkaline wastes unsuitable for ERW)**

Annually, 18 million tons of soda ash waste are produced (1.0 ton of Na_2CO_3 will result in 0.3 ton waste, with 62 million tons of Na_2CO_3 generated yearly).

These wastes have been accumulated over decades (e.g., see picture)
These wastes are already partially carbonated (this is taken into account in our calculation of CO_2 removal potential that is of several millions of tons yearly for this type of feedstock). These wastes are harmful to soils.

Figure 2. A soda ash disposal site in poland; ***Łuczak et al., 2021****)*

- **Alkaline minerals (like olivine) :**

These minerals can be mined and the global stocks could allow the mineralization of more than 1Gt of CO_2 per year. We however believe that the amount of industrial waste available should limit our use of alkaline minerals hence limiting the opening of new mines.

Our approaches to quantify CO_2 removal are multiple:

A direct method for quantifying CDR involves regularly measuring the biomass of the biomineralizing organisms in their culture system. By combining these measurements with the dry weight of individual organisms, we can determine their growth rate, the mass of $CaCO_3$ and organic matter produced, and subsequently calculate the mass of CO_2 converted into biominerals.

CO_2 removal quantification is further refined through geochemical analyses. By titrating the total alkalinity content in the culture medium and measuring pH and temperature, we can evaluate the specific concentrations of each dissolved inorganic carbon (DIC) phase, including CO_2 and bicarbonate. Direct measurements of CO_2 concentrations can be performed with several tools (e.g., Picarro, IR analyser, Eddy covariance flux towers). These parameters are routinely measured and input into a biogeochemical model (CO2SYS) that calculates the complete suite of parameters describing the carbonate system. By knowing the initial level of DIC in seawater, and how much we increase that level after adding alkalinity, we know how much CO_2 we sequester in seawater. We have a specific focus in the design of our farm to increase the air-seawater interface and thus ensure that all CO_2 removal due to alkalinity enhancement is happening within the walls of our facility.

By combining continuous measures of CO_2 removal in the medium and measures of the growth rate of the biomineralizing organisms, we can calculate the flux of CO_2 removed and biomineralized. At the laboratory scale, these measurements collectively determine the specific rate of CO_2 sequestration per unit biomass and area. These data are then extrapolated to estimate the potential CO_2 sequestration at the commercial scale.

Additional precise geochemical measurements are conducted on both the medium and the biominerals. For example, several chemical analyses on the biominerals themselves can inform on the conditions of their formation. This can be done long after mineralization, as these geochemical tools have been developed to understand the conditions in which carbonates formed million years ago in the sedimentary record.

These geochemical tracers measured in carbonates ($\delta 13C$, $\Delta 47$, B/Ca, $\delta 11B$, $\delta 18O$, Mg/Ca, trace elements, CAS concentration, $\delta 34S$) can inform us on many interesting parameters in the seawater at the time the mineral formed such as :

- The concentration of carbonate ions and the pH can inform us on the level of alkalinity enhancement in the media.
- The origin of the CO_2 mineralized (fossil or not).
- The temperature at which the crystals formed, that can, if that temperature is above local conditions, provide information on the energy consumption of the process.
- The type of trace elements released by the alkaline feedstock, informing us on the source of alkalinity used.

The development of these tools is a fundamental step in the scaling up of our MRV and could be useful for any mineralization approach.

Once CDR takes off, it will be extremely important for third parties to have a traceability framework of CDR combined with mineralization, and to be able to evaluate, without having to be in each facility, how additional was the carbonatation performed in the process in comparison to the natural level of carbonatation that would have occured on the waste pile. These geochemical measurements can tell whether biominerals were formed in conditions ensuring their carbon negativity in comparison to biominerals formed in nature, and which source of CO_2 was used.

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. 500-1000 words

Our five biggest risks are the following:

- **Technical risk:** Domestication

As with any cultivated species, domestication comes with higher growth rates and different properties of the organisms (in our case, it would be interesting to have organisms even denser in $CaCO_3$, for example). If it is too difficult to domesticate this family of organisms, we will face high costs. To avoid this problem, we are partnering with a company that specializes in the domestication of marine organisms.

- **Financial risk:** capex intensive

Our solution requires the installation of land-based cultivation systems. The investments are high and will be even more difficult to obtain as long as there are doubts about the possibility of the emergence of a viable permanent carbon credit market. To mitigate this risk, we are trying to be proactive and have participated in the creation of the French Association for Negative Emissions (AFEN) to promote CDR in Europe.

- **Defensibility:** We grow calcifying organisms present in nature

It is not easy to demonstrate that the biominerals we generate have been formed in conditions guaranteeing that they are carbon negative (as opposed to a culture system where alkalinity is not renewed). We are going to use geochemical tools to help us demonstrate that the seawater in which our organisms lived was ensuring CO_2 removal thanks to alkalinity addition. We are collaborating on this topic with several team of academics with expertise on carbonate geochemistry.

- **Project execution**: Scaling up marine organisms culture

Scaling up cultures of marine organisms can be challenging as a long "investment" period is necessary to spread the organisms, while we also need to collect as much as possible of these organisms to test their properties and produce our limestone powder. To be sure to scale up we need to follow the doubling time of the organism and continuously extend our cultures. We cannot pause our efforts during the first years if we want to achieve meaningful results for the climate. This can be hard when funding are scarce for exemple. This aspect however also means that what constitutes our CO2 binder and mineralization catalyser is self replicating and self improving.

- **HR**: We must create our own biomineralization industrial expert

Even though biomineralization is a common trait in nature, it is not yet a biotechnology. It means that the experts on this topic, able to work at the interface between marine biology and mineral chemistry, marine bioproduction and concrete manufacture do not exist yet. We are trying to be creative in the profile we recruit and hope to nurture a useful community of individuals ready to fight the environmental crisis, with the conviction that best solutions will come from an interdisciplinary approach.

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)*	350t
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	2027
Levelized cost ($/ton CO_2) *(This is the cost per ton for the project tonnage described above, and should match 6d)*	1357
Levelized price ($/ton CO_2)[3] *(This is the price per ton of your offer to us for the tonnage described above)*	1428

[3] 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).